

Color and Its Integration into U.S. Army Rotary-Wing Cockpits: A White Paper

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14. ABSTRACT Color is a perception arising from the response of the human visual system to light in the environment. This white paper attempts to provide discussions that reveal and explain the complexities of color, a natural, but frequently misunderstood, attribute of the human visual system. This endeavor is considered essential to ensuring the ever-increasing usage of color in U.S. Army cockpits (and throughout the Army) will in each instance enhance, not compromise, crew capability and performance, thereby increasing the probability of mission success. Its target audience is the myriad of professionals who design, implement, and evaluate the use of color in Army aeronautical systems.												
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Preface

This white paper was developed to provide a broad background for the ubiquitous but universally misunderstood phenomenon of color. While generally considered a physical characteristic of objects in the environment, color is actually an illusion and only exists in the mind. However, almost in contradiction to this statement, color (or at least color perception) is an important technique for encoding and presenting information. This is especially true in U.S. Army aviation, where color is greatly utilized.

This paper is intended to address the knowledge gaps that exist between the various factions involved in the planning, design, manufacture, and implementation of color in U.S. Army helicopter cockpits. To achieve this goal, a moderate but essential amount of background material is provided on the emergence, development, and application of color technologies across human history, as well as a discussion of how color is perceived and processed in the brain. While an emphasis is placed on color as an increasingly-used attribute of cockpit displays (panel- and helmet-mounted), there are additional color-related aviation issues, such as color vision standards and screening methodologies that are addressed.

The following persons, all of which have served at the U.S. Army Aeromedical Research Laboratory (USAARL), Fort Rucker, AL, and represent many areas of expertise (aviation, medicine, psychology, visual science, physics, and optometry) have collaborated to develop this white paper:

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an operational flying squadron before returning to medicine as a pilot physician and specialist in aviation medicine. He holds the Diploma in Aviation Medicine, MSc in Occupational Health, and Membership in the Faculty of Occupational Medicine. He was elected Fellow of the Aerospace Medical Association in 2015. He has served in a variety of roles in UK, Germany, Bosnia, Kenya and Belize. Also, he has served twice as a medical exchange officer at USAARL. His areas of research have included flight medicine, aircrew equipment development and integration, human factors, and aviation accident investigation both in the UK and U.S.

- Thomas H. Harding received his PhD in 1977 in Visual Neurosciences from Purdue University, Lafayette, IN. Past research positions include Visiting Scholar at the Biomedical Engineering Center at Northwestern University from 1975 to 1977 and Visiting Fellow at the John Curtin School of Medical Research at the Australian National University from 1977 to 1979. Since 1979, his career has been exclusively at USAARL, where he has held several key research and leadership positions, including Director, Division, and Senior Scientist. His research has focused mainly on helmet-mounted displays and other advanced optical systems, with particular emphasis on design considerations, image quality metrics, operational performance, and visual perception. He has been active in the SPIE Security and Defense Symposium for over 20 years as an author and/or conference co-chair.
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Introduction

The cockpits of U.S. Army rotary-wing aircraft (helicopters) have changed radically in the past two decades. Fast disappearing is the dedicated display (often referred to as steam gauge dial)¹ that presents specific, visual-only information. Today's choice of crew station displays by both designers and pilots is the full-color, multiple-page, programmable, multifunction display (MFD).² Such displays are represented as being sunlight-readable, night vision compatible,³ and capable of providing selectable, high-resolution navigation, (weapons) fire control, aircraft status, mission, and other data. These MFDs also can present real-time sensor imagery, e.g., radar, forward-looking infrared (FLIR), and image intensification (I²).

Even as more information can be presented via these panel-mounted MFDs, an adjunct display technology, the helmet-mounted display (HMD), has been adopted to allow pilots to fly head-up, eyes-out, by displaying pilotage imagery overlaid with limited aircraft status symbology.

Modern display technology in today's highly automated aircraft requires a different mindset and crew procedures for its efficient use as compared to the older steam gauge dial cockpits. With dedicated displays, the pilot has to integrate separate bits of information to arrive at a situation assessment and control strategy. With MFD's and HMD's, that assessment mostly is performed for the pilot and presented (if properly designed) in an intuitive color graphic format. The downside is that when using these displays, the pilot also has to be sure that what is presented is correct. How this is accomplished (integration) and what functions the pilot has to perform when accessing and using the automation can significantly increase cognitive work load and tax attention resources. Color may mitigate integration issues by helping to direct the pilot's attention to important information and actions that must be taken, and perhaps do a better job of drawing them into the real world. For example – a three-dimensional (3D) terrain display where a depicted mountain range ahead suddenly turns red, indicating potential collision with terrain if remaining at the current altitude. This directs the pilot's gaze to outside the cockpit and compels control action to avoid terrain impact (R. Ranaudo, personal communication, September 30, 2016).

As examples of these various display configurations, Figure 1 shows the U.S. Army's 1970's Kiowa OH-58A dedicated display cockpit (top, left), the 1980s Kiowa Warrior OH-58D "glass" cockpit⁴ with MFDs (top, right), the mid-1990s MH-47E Special Operations Chinook "glass cockpit" (bottom, left), and the Integrated Helmet Display Sight System (IHADSS) HMD (bottom, right) used in the AH-64 Apache attack helicopter first fielded in the 1970s.

Considered to be one of the most important capabilities of advanced displays in modernized cockpits is the ability to present a wide range of colors. Designers see two major

¹ The phrase "steam gauge dial" is generally used today in a derogatory manner, comparing modern electronic displays to older technology mechanical-based instrument dials used in steam-powered locomotives of the 1800s.

² Multifunction displays (MFDs) also are referred to as multipurpose displays (MPDs).

³ Night vision compatibility implies the display is compliant with Department of Defense Standard for Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible (MIL-STD-3009) (2001).

⁴ A *glass* cockpit is an aircraft cockpit that features electronic (digital) flight instrument displays, typically large flat panel screens (e.g., MFDs), rather than the traditional style of analog dials and gauges.

advantages to the implementation of “full-color”⁵ displays (Sobel, 1992). First, the increased number of colors is perceived as a means to encode and present more information. Second, there is the belief that full-color presentation of pilotage imagery is more realistic, and therefore more intuitive, to the pilot. While not requiring “full-color,” a third application of color is to differentiate items. The distinction between using color for differentiation versus information encoding is that clear identification is not required; it is sufficient that the different colors be reasonably distinct from each other (Sobel, 1992).



OH-58A



OH-58D



MH-47E



AH-64 IHADSS

Figure 1. U.S. Army’s 1970’s Kiowa OH-58A dedicated display cockpit (top, left), the 1980s Kiowa Warrior OH-58D “glass” cockpit with MFDs (top, right), the mid-1990s MH-47E Special Operations Chinook “glass cockpit” (bottom, left), and the Integrated Helmet Display Sight System (IHADSS) HMD (bottom, right) used in the AH-64 Apache attack helicopter.

These perceived major advantages have their origins in the innate familiarity humans have with color vision, the ability to distinguish between objects based on the wavelengths (or frequencies) of the light they emit, reflect, or transmit. With rare exception, humans perceive color in the environment almost from birth. Color vision matures at about the same rate as other visual capabilities (e.g., focus, tracking, and depth perception), obtaining a moderate degree of function within 2-4 months (American Academy of Ophthalmology, 2015).⁶ Similar to most elements of visual information, color is processed with no conscious awareness of its presence. It is not surprising that color vision and its usefulness are taken for granted.

⁵ The loosely-defined term “full-color” is frequently used in requirement specifications to describe the range of colors (color gamut) that a display must produce. For the purpose of producing color realism (natural color rendition), the term “true color” is used to define current SuperVGA 24-bit displays capable of producing 2^{24} (16,777,216) color variations.

⁶ Accuracy of color discrimination improves considerably between ages 4-6 years, reaching its peak between ages 20-30 (Goldstein, 2010).

Researchers believe color vision has an evolutionary basis, suggesting it serves important purposes (Bowmaker, 1998; De Valois & Webster, 2011; Gegenfurtner & Sharpe, 1999; Pinna & Reeves, 2015). These purposes include detection (locating), recognition, and identification of objects in the environment (Tanaka, Weiskopf, & Williams, 2001). In addition, the use of color has been shown to reduce reaction (or response) times for many tasks, an essential requirement in the cockpit (Balakrishnan et al., 2014; Breitmeyer & Breier, 1994; Holmes, 1926; Pollack, 1968; Lit, Young, & Shaffer, 1971; Nissen & Pokorny, 1977).

Historically, the idea that color, or at least the perception of color,⁷ is an important and desirable modality for the presentation of information has been a key driver in a number of commercial technologies. Classic examples include photography, movie production, television, and print advertising, where initial efforts were monochrome⁸ (black and white [B/W]), but where the achievement of color greatly increased the amount of information presented and therefore its effectiveness. It is understandable that display and aircraft crew station designers would similarly consider the increasing use of color in the cockpit to be an advantage.

While addressing the issue as early as the 1950s (Conover & Kraft, 1958), the military aviation community began to systematically investigate the use of color as an information coding method in the 1970s (Barker & Kregs, 1977; Barnes, 1970). However, while the addition of full-color displays to the cockpit certainly has many advantages and can be a potent tool for information communication, caution must be taken in its integration; if used incorrectly, color can be counter-productive at best and hazardous at worst. An otherwise good display design can be ruined by a haphazard use of too many colors or too vivid colors (Widdel & Post, 1992). Early guidance for use of color in MFDs was provided in the Society of Automotive Engineers (SAE) International's Aerospace Recommended Practice (ARP) Standard ARP 5364, *Human Factor Considerations in the Design of Multifunction Display Systems for Civil Aircraft* (2003), which states:

Studies indicate that the number of different colors that can be discriminated on a single display is generally limited to seven to nine colors. The reason for the limited number of colors is related to the human ability to discern color difference when the colors are too close together on the color spectrum. In some current displays, shading of colors can also indicate intensity, or some other gradation, such as in weather and terrain displays. The colors selected must demonstrate the ability to be distinguished easily and accurately under typical viewing conditions, especially during heavy workloads or stress.

In the last decade, expanded use of color in displays has drawn the attention of the human factors (HF) community and a number of guidelines have been developed.

For eyes-out HMDs, which are highly transparent devices, the use of color into the design can introduce a number of integration and performance issues (Fares & Jordan, 2015). A more generalized caution is provided by noted expert on the visual display of quantitative data Edward

⁷ For now, the term "color" is used in the colloquial sense, i.e., as a property of an object or surface. In later sections, color is described as not being an inherent attribute of objects, but is instead a visual perception formed in the brain. This understanding of color as an "illusion of the mind" and not a property of an object dates as far back as Aristotle (c350 BCEa, c350 BCEb), Galileo (1623), and Isaac Newton's (1672) experiments with light. Today, the concept of color falls mainly in the field of cognitive science.

⁸ *Monochrome* is commonly used to indicate black and white; however, the term is defined as a single color, which could be any color, e.g., red, yellow, green, etc.

Tufte (2001), who states that “...avoiding catastrophe becomes the first principle in bringing color to information: above all, do no harm.”

When first applied to aviation applications, it was expected that specific display formats using specific color codes could be easily developed (Krebs, Wolf, & Sandvig, 1978). However, it quickly became obvious that a single “ideal” color scheme was not possible. An effective solution was dependent upon a multitude of situation-specific factors; a good color scheme for one application could, in fact, be a poor one for another application.

Fortunately, with the proliferation of color in entertainment and advertising, many practical lessons have been learned about the application of color. Physiologists, vision researchers, and cognitive scientists have shown how many of these lessons can be explained by applying our ever-increasing understanding of the human visual system, which begins at the cornea of the eye and ends in the visual cortex in the brain.⁹ However, the human visual system frequently arrives at incorrect interpretations of the visual information entering the eye. These “illusions” can include perceptions of brightness, color, size, distance, and depth that are different from objective reality.

It would not be surprising that the frequency of illusions, or misperceptions, can be impacted by the operational situation or environment. The Army helicopter cockpit is a unique and highly-stressed environment. Pilots are subjected to fatigue due to long hours in a confined space requiring constant attention to cockpit displays presenting ever-changing flight status data and external hazards. They are subjected to acceleration, noise and vibration, altitude effects on the body, and the ever-present potential of mechanical, structural, and/or electronic malfunctions. In addition, the growing use of HMDs may introduce additional perceptual and cognitive effects in the presence of these external operational factors (Harding, Rash, & Lang, 2010).

It is well documented that operational stressors in the military aviation environment degrade cognitive function (Rash et al., 2010). This complex myriad of stressors puts pilots at risk for psychological trauma and mental difficulties including problems of memory, perception, and cognition. The result is pilots are more likely to commit mental errors. This is borne out by accident statistics for military operations that show approximately 70-85% of all catastrophic mishaps are caused by human error (Wiegmann & Shappell, 2003).

To ensure that the integration of color into the cockpit does not introduce additional perceptual and cognitive issues, it is important that everyone involved in the hardware development, crew station design, and color strategy have a sufficient understanding of color theory, as well as of human color vision. Unfortunately, color is a complex topic that to be used effectively must include a basic knowledge of three major fields of study: physics, physiology, and perception (Widdel & Post, 1992).

Physics explains the various mechanisms responsible for the generation of the spectral components of the light emitted or reflected by objects in the external world. Physics also defines the optical laws that govern the collection and focusing of this light onto the back of the eye. The

⁹ The processing of visual signals from the retina actually involves a number of cortices in the brain, to include the primary and secondary visual cortices.

measurement of the spectral power distribution (SPD) of the light arriving at the eye also falls under the purview of physics. *Physiology* explains how this optical image formed on the retina, a layer of photoreceptors (rods and cones), is converted into an electrical signal carried by the optic nerve to the brain, chiefly to the primary visual cortex, via a “relay center” known as the lateral geniculate nucleus (LGN); this is the process of sensation. *Perception* is the multifaceted process of becoming aware of objects via sensory signals from the various sense organs (e.g., eyes, ears, skin) resulting from external stimuli and making interpretations of these signals, in essence forming a representation of the external world and the objects in it. Specifically, *visual perception* is the facet of perception that interprets the surrounding environment by processing information contained in visible light via the eyes.

Fortunately, human factors engineering (HFE) efforts, which combine the knowledge of many disciplines, have achieved some success in educating hardware and software designers to the necessity of addressing physical, physiological, perceptual, and cognitive characteristics in the design of devices and systems for human use. These efforts have produced a number of guidelines regarding the use of color in displays (Cardosi & Hannon, 1999; Malamed, 2011; Marcus, 1995; Murch, 1995). Nevertheless, the availability of these guidelines has not guaranteed their use, and there is still a persistent failure to apply good HFE practices in some applications of color. A major underlying reason for this failure is that designers, developers, and users continue to fail to fully consider the interactions between the physical, physiological, and perceptual attributes of color. Widdel & Post identified a major shortcoming of many color guidelines to be an overemphasis on the physical characteristics of color (1992).

In the operational community, there is the belief that the use of color for displays should have a specific goal. For example, one modern wind shear alerting and control display uses color guidance cues, where the color of the guidance cues (red or amber¹⁰) provides both meaning and sense of seriousness and urgency at a glance. This integration elicits better situation awareness, crew reaction time, and anticipatory control inputs. If a monochrome display is used, some other means of conveying this information such as text would require more time to interpret the situation, slowing pilot reaction. Developing guidelines for the use of color should be task related and address the urgency of better performing these tasks for safety and mission purposes (R. Ranaudo, personal communication, September 30, 2016).

This white paper¹¹ has two major goals. The *first* goal is to provide a broad review of the major tenets of the different interpretations of color. This is intended to address the knowledge gaps that continue to exist between the various factions involved in the planning, design, manufacture, and implementation of color in U.S. Army helicopter cockpits. While this paper has an emphasis on color as an increasingly-used attribute of cockpit displays (panel- and helmet-mounted), there are additional color-related aviation issues, such as color vision standards and screening methodologies that are addressed.

The first faction includes Army flight surgeons, research optometrists, physiologists, and visual psychophysicists. The first three of these groups of individuals fully understand the

¹⁰ The color amber is a pure chroma color, located on the color wheel midway between the colors of gold and orange.

¹¹ This paper adheres to the classic definition of a white paper as a guide that concisely presents a complex issue and the issuing body's philosophy on the subject. Its purpose is to assist its audience in understanding a concern, solving a problem, or making a decision; it may advocate a specific position on a subject or solution to a problem.

anatomy and physiology of the eye and the underlying principles of color vision, and most likely have a moderate, experience-based understanding of visual perception; conversely, the fourth group, visual psychophysicists, while having an excellent understanding of visual sensation and perception, may not have an as equally strong background in visual anatomy and physiology. What many individuals across all of the groups may lack is training in the myriad physics and engineering concepts involved in color display systems, which includes how color is generated, as well as the hardware (e.g., light sources and optics) and the underlying color presentation strategies implemented via software.

Another faction consists of the U.S. Army's physicists and engineers. These individuals play huge roles in the development, testing, and evaluation of display systems. By profession, they have a comprehensive background in the physics and engineering of color and the design of displays. However, with the rare exception, these individuals have little training or experience with physiology and visual perception.

A third faction is made up of the software and hardware engineers, system designers, and project managers of the commercial defense and aerospace companies that design and manufacture avionics equipment for the military. While in decades past these companies were more decidedly inclined toward a physics and engineering approach to system development and slow to adopt emerging HFE principles, they have undergone tremendous changes in their methodology over the last two decades. They now incorporate HF requirements during the earliest stages of programs and have adopted development approaches that include the human-in-the-loop.¹² Nonetheless, today's exponential growth in engineering and technology (which includes the explosion of color displays) often outpaces the understanding of the interaction of technology and the human user, resulting in products that fail to deliver the expected performance improvement. Examples of overlooked, or at least poorly-considered, factors that impact the success of new technology include ergonomic concerns (e.g., fatigue and comfort), user expectation (utility) and acceptance (usability), initial training and skill retention requirements, and ease of use (Arvanitis et al., 2011; Hinchcliffe, 2013; Richardson, 1987).

The last faction is the user community, consisting of the organizations responsible for generating Operational Needs Statements (ONS)¹³ and aviation technical and functional requirements, and the pilots themselves.¹⁴ ONSs, by definition, grow out of problems, requests, and needs generated by the user community. Today's technology boom may lead to situations where "wants" exceed "needs." Additionally, there may be an overextended trust in technology that prevents users from recognizing human performance capabilities and limits (Institute of Cognitive Sciences and Technologies, 2015).

This first goal, intended to raise awareness of the complex nature of color among all factions involved in design and development programs, as well as in fielding endeavors, is undertaken in the *Background* section. This section begins with a discussion of the physics and chemistry of color. This is followed by a review of the major concepts of color science, which

¹² *Human-in-the-loop* is defined as a model that requires human interaction.

¹³ An Operational Needs Statement (ONS) is a request for a materiel solution to an operational requirement to correct a deficiency, improve an existing capability, procure a new/emerging capability, or ensure mission accomplishment.

¹⁴ There cannot be "too much" emphasis placed on pilot input. While much progress has been made in including the user community in new system programs, many design decisions are still made without being vetted by the primary user, the pilot.

include color wheels, color properties (hue, saturation, and brightness), additive and subtractive mixing theories, color spaces, and colorimetry (measurement of color). Next, a timeline of milestones in the ascent of color as a method of encoding and reproducing information is presented, with the obligatory discussions of color technologies. In the subsequent section, the role of color in human culture and its use in symbolism is presented. Next is a focused discussion of the use of color in aviation. Then, the anatomy and physiology of color vision and the fundamental principles of color perception are discussed. This is followed by a brief review of color vision screening (testing), its history, equipment, and methodologies, as well as standards used by the military services. The *Background* section concludes with a brief summary of the most important HF guidelines for designing and implementing color strategies in avionics equipment, especially displays, as well as a look at the future of color use and technologies.

Because achieving this first goal requires a presentation of the basic tenets of color concepts from the perspective of multiple disciplines, this section is considerably greater in length and wider in scope than in a typical research paper. In an attempt to provide the reader with the broadest understanding of the complexity of color and human interaction with color, historical context has been provided for most color topics. In addition, this section incorporates a large number of footnotes that the authors believe adds depth to subject matter and in doing so provides a wider scope for understanding color. Finally, because color is such a multifaceted and multi-disciplined subject and there is such an interlinking of topics, many different approaches to the order and organization of topics presented in the *Background* section are possible. The sequence adopted hopefully is one that successfully achieves the goals of this white paper. The interlinking of topics also results in the necessity of the repeating of some major color tenets in order to provide context.

Following the *Background* section is a section titled *Color in U.S. Army Rotary-Wing Crew Stations*, which is a discussion focusing on the use of color in U.S. Army helicopter cockpits. Critical to this discussion is a brief history of why and how color was integrated into what is today the Army's all-helicopter aviation force.¹⁵ Examples of current crew station designs employing color MFDs are given. Several color issues special to Army aviation are explored. These are: Aviator's Night Vision Imaging System (ANVIS)¹⁶ lighting compatibility, monochromatic imagery via HMDs, and viewing MFDs through tinted protective visors. One of the most interesting of these special issues is the use of narrow-band phosphors for image generation in the Army's HMDs (Harding, Rash, & Lang, 2010). While afterimage effects associated with these systems have been reported and investigated since the early 1970s (Glick & Moser, 1974), a later study looked at the possible confounding which might occur when aviators must view color cockpit displays intermittently during prolonged ANVIS use investigation (Moffitt, Rogers, & Cicinelli, 1988). Their findings suggested degraded identification of green and white colors on such displays, requiring increased luminance levels. This section concludes with a discussion of the potential that color could be a causal factor in some accidents.

The *second* goal of this white paper is to identify: a) color-related issues that are known to, or potentially may, impact U.S. Army helicopter pilot performance and safety; b) potential

¹⁵ While the vast majority of U.S. Army aircraft are rotary-wing (helicopter), the Army does have a small number (~ 375) of fixed-wing aircraft that include the C-12, C-26 and UC-35, which are classified as transport aircraft, and a few special mission intelligence gathering aircraft.

¹⁶ Commonly known as Night Vision Goggles (NVGs), these devices operate on the principle of image intensification (I²); outside of the U.S. Army, ANVIS devices is more generally known as the Integrated Night Vision Imaging System (INVIS).

topics for future research to improve the use and integration of color in military aviation. The methodology used to identify these issues and topics included a literature review, the application of over five decades of aeromedical vision science research experience at the U.S. Army Aeromedical Research Laboratory (USAARL),¹⁷ Fort Rucker, AL, and collaborative discussions with the user community.

This catalog of issues first includes the obvious physiological conditions of congenital color defects, ocular diseases and injuries, and aging effects on vision that form the basis for the selection criteria for entry into pilot training, as well as for continuing to meet annual flight physical requirements (Gradwell & Rainford, 2015). Other high profile issues closely aligned with the color vision screening for the military pilot population include outdated color tests, poor adherence to defined screening procedures, and lack of occupational testing standards (Kirkendall, 2013; Reddix et al., 2014).

The next and perhaps the greatest area of interest and concern is of color perceptual issues. The ability to perceive different colors in the environment leads to a number of advantages. Color and color combinations play an important role in detection and identification of specific objects or classes of objects (Derrington et al., 2002). The use of color seems to improve memory performance and, hence, information retention (Bergeron, 1990; Dzulkifli & Mustafar, 2013; Spence, Wong, Rusan, & Rastegar, 2006; Wichmann, 2002). In addition, color is a strong driver of attention. Attention refers to the cognitive process of selecting and attending to specific information present in the environment. The level of attention directed to certain stimuli increase the probability of the information to be stored in memory (Smilek et al., 2002; Pan, 2012). In aviation, attention is really important, especially in time critical situations where an impending safety issue or performance loss can impact successful mission completion (R. Ranaudo, personal communication, September 30, 2016).

And, while color is itself an illusion, there are a number of visual situations (e.g., metamerism,¹⁸ lateral inhibition,¹⁹ color constancy,²⁰ color afterimage,²¹ and color-induced illusory motion²²) that involve color perception and are commonly referred to as color illusions.

The last group of issues relate to the impact of operational conditions, e.g., visor wear, hypoxia, laser glare, high acceleration (in the AH-64 Apache), and aviation environmental factors (i.e., exposure to fuel vapor and chemical agents) on color vision (Rash et al., 2010).

¹⁷ Established in October 1962 to provide aviation medical research support to all Army aviation and airborne activities, USAARL has been involved with most medical aspects of vehicular occupancy, airworthiness testing, air safety, occupational hazard exposures, and personal protective equipment. In addition, USAARL has researched topics such as vibration, jet lag and fatigue, tinnitus, helmets, visors, night vision goggles (NVGs), helmet-mounted displays (HMDs), seats and restraints, and spatial disorientation. Visit <http://www.usaarl.army.mil>.

¹⁸ In colorimetry (the measurement of color stimuli), metamerism is the matching of the apparent color of objects with spectral power distributions that differ from one another. Colors that match this way are called metamers.

¹⁹ *Lateral inhibition* is a visual mechanism that enhances the contrast of the outline of an object. For colored objects, when a photo-receptor from one area of the retina becomes stimulated by a color, those next to it become less sensitive to that color.

²⁰ *Color constancy* is a subjective feature of human color perception that ensures that the perceived color of an object remains relatively constant under varying illumination conditions.

²¹ *Color afterimages* are caused by an increased sensitivity of the lesser excited photoreceptors in the retina, a process incorrectly called photoreceptor "fatigue." The process causes complementary colors to be seen in afterimages.

²² A constant change in color can produce illusory motion, which is defined as the appearance of movement in a static image.

Background

Humans receive information about the external world via a number of sensory systems (senses). Classically, there are five major senses – sight (vision), hearing (audition), touch (haptics), smell (olfaction), and taste (gustation). However, there are a number of other senses that provide information, e.g., the vestibular system (balance and body posture), which incorporates proprioception (relative position of body parts) and kinesthesia (movement of the muscles, tendons, and joints); nociception (pain); and thermoception (heat and cold).

Vision appears to be the dominant sensory system as it uses approximately 30% of the brain's cortical regions (the cerebral cortex),²³ as compared with 8% for touch and just 3% for hearing. The two optic nerves, which carry signals from the retina to the brain, each consists of approximately 1.2 to 1.7 million fibers (Jonas, Schmidt, Muller-Bergh, Schldrzer-Schrehardr, & Naumann, 1992; Grady, 1993);²⁴ in comparison, each auditory nerve has only 30,000 fibers (Augustine, 2008).²⁵ The visual signal leaving the retina carries information that allows humans to detect objects, identify shapes, detect relative motion, gauge distance and speed, judge the size of faraway objects, and see “color.” The result is a unified visual perception that is a representation (or mental model) of the surrounding world.

This visual perception of the world is just that...a *perception*. The optic nerve does not have channels (i.e., bundles of fibers) that are dedicated to specific types of visual information, e.g., size, shape, luminance, or color. Only one type of sensory signal traverses the optic nerve.²⁶ This signal is the spatial distribution of the intensity of the light energy that enters the eye, and the brain uses this information to build a picture of an external scene.

Individual photoreceptors indicate only the rate at which they absorb photons, with no regard to individual photon wavelengths (which are associated with color). Though changing the wavelength of a photon changes its probability of being absorbed, it does not change the neural effect that it has once it has been absorbed. Therefore, individual photoreceptors transmit no information about the wavelengths of the photons that they absorb. Instead, the ability to perceive color depends upon *comparisons* of the outputs of the three cone types, each with a different spectral sensitivity. These comparisons are performed by the neural circuitry of the retina.

The attribute of color may be the most perplexing of all the attributes of the visual experience (Mausfeld, 1998). This arises from color not being a physical characteristic of

²³ This percentage varies greatly in the literature, from as little as 20% to as much as 60%. The question is a difficult one as many sections of the brain are involved in multiple functions, with motor, attention, spatial navigation, and other functions interacting with vision. Researchers at the Massachusetts Institute of Technology (MIT) cite at least 50% of the human brain is involved directly or indirectly with visual processing (MIT, 1996); researchers working with the Neuro-Optometric Rehabilitation Association estimate that 80-85% of human perception, learning, cognition, and motor activities are mediated through vision (Politzer, 2009).

²⁴ This number is low compared to the roughly 130 million receptors in the retina, and implies that substantial pre-processing takes place in the retina before the signals are sent to the brain through the optic nerve.

²⁵ Nonetheless, *color* vision may be considered inferior to hearing (audition) in the sense that individual frequencies of sound can be heard, but separate frequencies (wavelengths of light can't be seen (Hurlbert, 2002).

²⁶ The optic nerves also conduct visual impulses that contribute little or nothing to (image-forming) vision but play a role in maintaining the circadian rhythm or are responsible for two important neurological reflexes: the light reflex of the pupils and the accommodation reflex (near/distant focusing).

objects, but rather a subjective inference of the viewer.²⁷ There is strong anthropological evidence that color labels (names) have emerged through cultural evolution (Kay, 2003; Bornstein, 2007; MacLaury, Paramei, & Dedrick, 2007). With rare exceptions, all cultures seem to have developed a common hierarchy of color names (Loreto, Mukherjee, & Tria, 2012), which begins with names for black-dark and white-bright. If a culture has three color names, the third is always red; a fourth name is consistently yellow or green; and blue is the last of the principal colors to be named.²⁸ Some color names are strongly tied to objects in nature. Red is associated with blood, either human or of a slaughtered animal, and yellow and green with grass/vegetation.²⁹ In ancient Greece (c350 BCE), the philosopher Aristotle, who is credited with the first theory of color, identified seven colors based on relative darkness and lightness: black, deep blue, green, violet (or purple), crimson (or red), yellow (or gray), and white. He associated some of these colors with the four basic elements: earth (black), fire (white), air/wind (red), and water (yellow) (Kuehni, 2003; Clarke & Baccianti, 2014). Almost two millennia later (c.1490), the scientist, inventor, and artist Leonardo Da Vinci presented a theory of color based on six colors in the following order: white (representing light), yellow (earth), green (water), blue (air), red (fire), and black (representing darkness) (Varley, 1980).

Beyond these ancient basic color names, color nomenclature development gets more complicated (Wood, 1905; Kay & Maffi, 1999). Berlin & Kay (1969) claim there are eleven universal color groups, and all languages draw their list of color labels from this universal set: red, green, yellow, blue, pink, brown, purple, orange, and three achromatic terms, black, white, and gray (Boynton & Olson, 1990). There is some general agreement among scholars that most individuals name the numerous colors in their environment using about a dozen color terms (Berlin & Kay, 1969; Lindsey, Brown, Brainard, & Apicella, 2015). For the English language, several studies have shown agreement on the most used color names, which include in decreasing frequency: purple, pink, blue, and green (Moroney, 2003; Mylonas & MacDonald, 2010). However, the question of culture and color names continues to be an active topic of discussion as electronic displays have become ubiquitous and capable of producing millions of colors (Berk, Kaufman, & Brownston, 1982; Conway, 1992; van de Weijer, Schmid, Verbeek, & Larlus, 2009).³⁰ Researchers believe that color lexicons grow from fewer to more color names as technology advances and color communication becomes progressively important (Kay & Maffi, 1999; Lindsey, Brown, Brainard, & Apicella, 2015). A number of efforts to bring organization to the naming of colors have been undertaken. Two of the most significant were *The Inter-Society Color (ISCC)-National Bureau of Standards (NBS) Method of Designating Colors and A Dictionary of Color Names* (Kelly and Judd, 1955) and *A Universal Color Language* (Kelly, 1965). Both of these works were consolidated as U.S. NBS' *Color – Universal Language and Dictionary of Names* (Kelly, 1976). The latter publication repeats the descriptions of the selection of the ISCC-NBS hue names and descriptive modifiers of the lightness and saturation of a specific color provided in the original documents, as well as the 1965 introduction of color centroids, but also updates where revisions in color science nomenclature were needed.

²⁷ Saying that color is not an attribute of an object is not the same as saying that the light emitted or reflected by an object does not have a color characteristic. This is expanded upon in the discussion of the *Physics and Chemistry of Color* section.

²⁸ As a name, the color blue seems to be absent in ancient languages and appears to first emerge in the Egyptian and Byzantine civilizations sometime before 1300 B.C. (Serman, 2012).

²⁹ While it may be tempting to think that blue was associated with the sky, actually this color was used to represent heaven or, in classical mythology, various gods.

³⁰ True-color (24- or 32-bit) displays are capable of as many as 16.8 billion colors (Lynch & Horton, 2008).

The word “color” itself and its fundamental concept evoke a wide range of responses, which usually depend on how color is encountered in day-to-day activities. Difficulties and the confusion that regularly arise in discussing color and addressing color issues almost always can be attributed to the failure to identify the context in which the color concept is being employed. The eminent color scientist Deane B. Judd³¹ (1979) stated that “nearly everyone knows a good deal about some phase or other of color,” but being a “color expert” would demand the ability “to discuss chromophores with the chemist, mordants³² with the (fabric) dyer, spectrophotometric curves with the physicist, color specifications with the engineer, and color sensation and perception with the psychologist.”³³

For many individuals, color is thought of in the context of aesthetics or beauty, e.g., sunsets, flowers, rainbows. Color is an important factor in the selection of cars, clothes, and even food. Artists rely strongly on this color connection to create harmony and evoke emotion in their artwork. Psychologists consider color as a non-verbal communication that depends on culture and circumstance and has a profound effect on human response and behavior (Adams & Osgood, 1973; Sakamoto, 2014). Advertising specialists leverage off these responses in order to create or influence desire for various products (Wright, 1995; Grossman & Wisenblit, 1999). The French painter Paul Cezanne (1839-1906) is quoted as saying “Colour is the place where our brain and the universe meet (Doran, 2001).”

To flight surgeons and physiologists, color is the result of the response of the specialized photoreceptors called cones in the eye’s retina. There are three types of cones, each containing a photo-pigment with a different spectral sensitivity (response) to light. However, a cone responds only to the total energy (number of photons) it absorbs (Wolf, Kluender, & Levi, 2006). Therefore, multiple combinations of wavelengths of light can produce identical responses from a cone if the energy absorbed is the same. This principle of univariance implies that individual cones are effectively color blind, i.e., no single cone can identify a specific color. Instead, color vision results from comparisons between the three types of cone responses that occur in the brain. As a result, cognitive scientists state that color, as an inherent characteristic of an object, does not exist, but is instead, a perception. This concept of color confirms the idea that there is no such thing as “redness” or “greenness” as an attribute of objects.³⁴

This argued nonexistence of a color attribute is reinforced by visual experiences where the apparent (or perceived) color of an object varies with object illumination, viewing geometry, as well as with the chromatic properties of the surrounding environment. However, for expedience, it can be argued that only the light entering the eye from an object contributes to what “color(s)” is “seen,” although still subject to experience and memory effects.

Underlying all of these responses to the presence of color is the universal recognition that perceived color frequently is associated with information. In fruit, red apples and yellow bananas

³¹ Physicist Dr. Deane Brewster Judd (1900-1972) spent over 40 years at the National Bureau of Standards (NBS), Washington, DC, developing techniques and standards in the field of colorimetry. He published more than 200 papers, making important contributions to the understanding of color science and color vision. He was the American representative to eight meetings of the International Commission on Illumination (CIE), spanning four decades.

³² A *mordant* is a substance, typically an inorganic oxide, that combines with a dye or stain and thereby fixes it in a material.

³³ A *chromophore* is the part of a molecule responsible for its color, which arises when a molecule absorbs specific wavelengths of visible light and transmits or reflects others. A mordant is a substance (e.g., an inorganic oxide) that combines with a dye to set it in a material.

³⁴ While this approach to color has widespread acceptance among vision researchers, it is not without its detractors (Noe, 2004), who argue for color physicalism, which holds that color is defined by surface spectral reflectance (Byrne & Hilbert, 2003).

indicate ripeness; green, yellow, and red in traffic signals indicate allowable actions; yellow and red flags on the beach warn of surf conditions. In aviation displays, green, amber (yellow) and red are used universally for status indications of normal, caution, and warning, respectively. Color provides an additional method by which information can be presented or reinforced. Color can be used to draw attention to information, improve visual search speed, improve object recognition, indicate change in conditions, convey structure, show association, improve organization, present symbolism, establish identity, promote understanding, and encode qualitative or quantitative information (McDougall & Osborne, 2006; Malamed, 2011; O'Donnell, Colombo, & Boyce, 2011). The integration of color into cockpit displays, both panel- and helmet-mounted, can potentially provide one, or any combination, of these functions.

Physics and Chemistry of Color

As emphasized previously, color is not an attribute of objects. However, it is an attribute of the light emitted, transmitted, and/or reflected by an object. The perceived color(s) of an object depends on both the physics of the object, the illuminating source, its surrounding environment, and the characteristics of the observer's visual system, i.e., eye and brain. Physically, objects can be said to have the color(s) of the light leaving their surfaces, which depends on the spectra of the emitted energy or incident illumination and the reflectance and transmittance properties of the object, as well as potentially the angles of illumination and viewing. In the following discussion, it will be shown that from a physics perspective, "color" results from an imbalance of visible energy reaching the eye, an imbalance being defined as any deviation from the average amount of energy at all wavelengths (Godfrey, 1999). A colored light source is one that radiates more visible energy at certain wavelengths than at others; a reflective or transparent colored object reflects or transmits, respectively, certain wavelengths more than others (Serway & Faughn, 1999).³⁵

In most generalized discussions of light, the term is assumed to refer to *visible* light. In reality, visible light is a small band of the larger electromagnetic (EM) spectrum consisting of the full range of EM energy waves (Figure 2). The EM spectrum typically is divided into seven bands that include (from high to low energy): gamma rays, X-rays, ultraviolet (UV), visible, infrared (IR), microwaves, and radio waves.

EM waves are created by electric charges undergoing acceleration or when electrons bound within atoms or molecules make transitions to lower energy states, as in the case of visible light (Hulsizer & Lazarus, 1972).³⁶ For accelerated electric charges, the frequency of the resulting EM wave depends on the acceleration value and how it changes with time. For example, if a charge oscillates in simple harmonic motion at a frequency of 3,000 cycles per second, it will produce an EM wave of 3,000 hertz (Hz) (3 kilohertz [kHz]),³⁷ which is in the radio band of the EM spectrum. This is exactly the method used to produce radio waves used in wireless communication, where an alternating current produces accelerating electron charges in a radio antenna.

³⁵ An extreme case of imbalance would be a pure monochromatic situation where a single wavelength of visible energy, or color, is present (Godfrey, 1999).

³⁶ The discovery by James Clerk Maxwell in 1860-1865 that visible light consists of EM waves is considered to be one of the major accomplishments of the field of physics (Beiser, 1992).

³⁷ The number of oscillations, or cycles, of a source per second is called the *frequency* of the source, which usually is the frequency of the waves it generates. The unit of frequency is cycles per second or hertz (Hz).

Visible light generally is cited as including frequencies from approximately 4×10^{14} Hz to 7×10^{14} Hz. While physicists use frequency to identify specific EM waves, most other disciplines use wavelength.³⁸ Therefore, the frequency range of visible light alternately can be expressed as the wavelengths of 400-700 nanometers (nm).³⁹

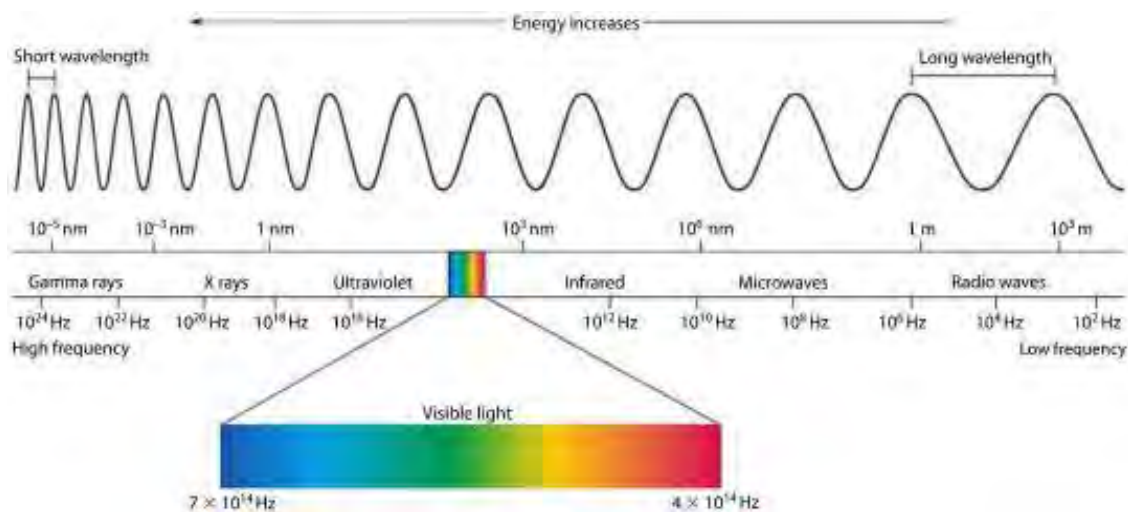


Figure 2. Visible light as a band within the full electromagnetic (EM) spectrum.⁴⁰

No ordinary mechanical oscillations of charged electrons can achieve the high frequencies (or low wavelengths) of the visible spectrum; only the motion of charged electrons inside atoms and molecules can obtain such frequencies. However, most of the visible light commonly encountered in the everyday world is the result of transitions of the outer electrons in atoms from higher to lower energy states (Tipler & Mosca, 2004). Via a number of processes that increase the energy in an atom, the outer electrons can be excited to higher energy states. In a time as small as nanoseconds, these excited electrons will spontaneously make transitions to lower energy states. In doing so, a photon⁴¹ of light will be emitted. The energy of the emitted photon is equal to the energy difference between the initial and final states. The wavelength (λ) of the emitted light is defined by Einstein's equation, $\lambda = hc/\Delta E$, where h is Planck's constant (6.626×10^{-34} joule-seconds),⁴² c is the speed of light in a vacuum (3×10^8 meters/second), and ΔE is the energy difference between the transitional states.

³⁸ For EM waves, frequency and wavelength are related by the simple equation $\lambda f = c$, where λ is the wavelength, f is the frequency, and c is the speed of light in a vacuum (3×10^8 meters/second).

³⁹ The visible spectrum is by definition the range of wavelengths the "typical" human eye responds to. In the literature, this range is not uniquely defined and varies to as low as 380 nm at the lower limit and to as high as 780 nm at the upper limit (Barnes, 1994; Cesare, 1987; Lapedes, 1978).

⁴⁰ Important note: Colors presented in this paper are provided for general color information and illustration purposes only. Because of the differences in computer monitors, printers, and other hardware and software combinations, depicted colors are intended to be used as approximations, rather than definitive representations.

⁴¹ Photon is the name given to a packet of visible EM energy; it is also referred to as a particle of light. The concept of a photon was introduced by Albert Einstein as part of his quantum theory of light.

⁴² Max Karl Ernst Ludwig Planck (1858-1947) was a German physicist who originated quantum theory, for which he was awarded the Nobel Prize in physics in 1918.

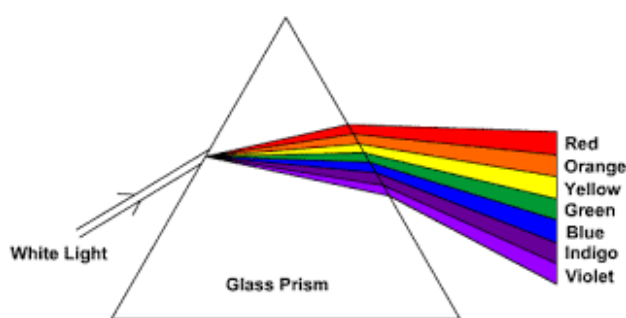
Before expanding in greater detail on the various light production mechanisms, the visible spectrum requires further discussion, specifically the relationship of color to the visible spectrum band.

The visible spectrum.

It is very likely that one of the first experiences with the visible spectrum was viewing the colors present in a rainbow, which is the result of the refraction and dispersion of sunlight by water droplets in the atmosphere (Figure 3, left). In a series of experiments conducted in the late 1660s with a prism, Isaac Newton demonstrated that “white” light from the sun actually was composed of the various colors seen in rainbows,⁴³ a result of the refraction of light by the prism (Figure 3, right). Refraction is the bending of light when it crosses from one medium into another where its speed is different. As light passes through a prism (air into glass and back into air), it is refracted by the faces of the prism, with each wavelength of the light refracted by a slightly different amount. Violet has the highest frequency and is refracted the most; red has the lowest frequency and is refracted the least. Because each wavelength (color) is refracted differently, the incident white light is spread out and separated into the colors of the visible spectrum.



Rainbow



Newton's prism

Figure 3. A rainbow created by the dispersion of sunlight by water droplets (left) and Newton's use of a prism's refractive properties to produce a visible spectrum from sunlight (right).

The separate color bands in rainbows and produced by prisms are an artifact of the human visual system (as color is a perception), and they are not as distinct as presented in the diagram of Newton's experiment (Figure 3, right). Rather, the bands are continuous as presented in the lower part of Figure 4, a representation of the visible spectrum. However, the different colors (hues)⁴⁴ are apparent enough that Newton used them to present a color theory in the form of a wheel (also known as Newton's color circle) in 1666 (Figure 5) (Newton, 1704).⁴⁵ A color wheel is really just the spectrum twisted around so that the violet and red ends are joined. Newton compared colors in the spectrum to a run of musical notes. He divided the color wheel

⁴³ Newton was not the first to observe spectrums produced by refraction through glass; the production of colors from light passing through glass spheres or pieces of broken glass was widely known in the Middle Ages (Shapiro, 1994) and observed by Aristotle in ancient times (Neuenschwander, 2014). The Italian Jesuit Priest Francesco Grimaldi (1665) had observed colors during his groundbreaking discovery of diffraction in 1665. However, prior to Newton, it was generally accepted that the dispersion of the white light into colors was due to a property of the glass (prism).

⁴⁴ The term *hue* is one of the main properties of a color. Hues correspond generally with color names, e.g., red, green, and blue. Hues can be associated with specific locations on the visible spectrum. Each hue is directly defined by its wavelength.

⁴⁵ Newton's work on this topic mostly was performed in 1664 to 1666 but was not published until 1704 in *Opticks*.

into musical proportions around the circumference, represented by arc segments. Each segment represented a different spectral color, starting from red, through orange, yellow, green, blue, and indigo, to violet.⁴⁶ The arc segments are unequal because they are based on the proportion of each wavelength in the spectrum relative to the others. The center of the wheel, point O, represents the “white” light source composed of all the wavelengths (Feisner, 2006).⁴⁷ To aid in remembering the colors of the visible spectrum, the acronym ROYGBIV (or *Roy G. Biv*) often is used (Figure 4).

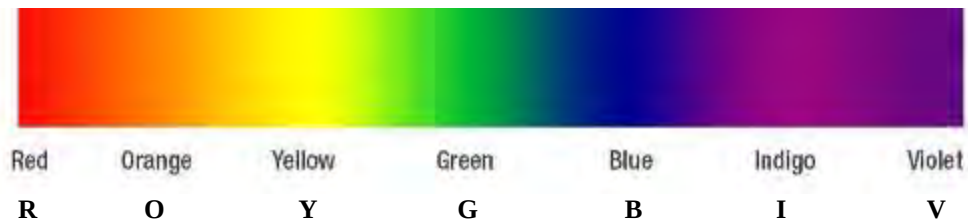


Figure 4. The acronym *Roy G. Biv* is used as an aid to remember the colors of the visible spectrum: red, orange, yellow, green, blue, indigo, and violet.



Figure 5. Newton's color wheel (Newton, 1704).

While there is no clear delineation between colors (wavelength bands) of the visible spectrum, artificial boundaries are frequently cited for discussion purposes. Table 1 gives an example of one such description (The Huris Group, 2012). (*Note:* Representative colors with Red, green, and blue (RGB) color space values are presented in the first column of Table 1. See discussion of RGB and other color spaces in a subsequent section, *Color Science*).

⁴⁶ Newton's choice of seven segments, or colors, was not based on observation but rather on his belief that music and color were in harmony. In music theory, each octave has seven tones and semitones (Lee & Fraser, 2001).

⁴⁷ Newton's color wheel is based on the *additive* mixing system of colors. This is the system associated with mixing various colors of light. An alternate system, known as the *subtractive* system, is associated with the mixing of paints or inks. These two systems are discussed in a later section, *Color Science*.

Newton's investigation of color was primarily from the perspective of physics. When human perception, i.e., vision and hearing, is considered, his belief that color theory correlates to music theory is easily invalidated. If any number of color lights is combined, the visual perception is of a single color. For example, a mixture of green and blue light is perceived as yellow, even though there is no actual contribution from wavelengths in the yellow part of the

Table 1. Example of wavelength bands associated with the major colors in the visible spectrum.

RGB value ⁴⁸	Color		Wavelength band (nm)
255, 0, 0	R	Red	620-750
255, 165, 0	O	Orange	590-620
255, 255, 0	Y	Yellow	570-590
0, 255, 0	G	Green	500-570
0, 0, 255	B	Blue	450-500
75, 0, 130	I	Indigo	420-450
238, 130, 238	V	Violet	380-420

Note: RGB values are sourced from <http://cloford.com/resources/colours/500col.htm>

spectrum. However, humans can listen to a full symphony orchestra and easily separate the different types of instruments from the single acoustic pressure wave arriving at the ear (Nassau, 1983).

To be comprehensive in a discussion of the visible spectrum, it is necessary to point out studies have shown some individuals do experience a visual sensation to IR stimuli (continuous laser)⁴⁹ at wavelengths as high as 1064 nm (Griffin, Hubbard, & Wald, 1947; Sliney, Wangemann, Franks, & Wolbarsht, 1976; Tilton, 1979; Palczewska et al., 2014) and to UV stimuli (300 to 400 nm) if of great intensity (viewed as a whitish-violet or whitening blue shade) (Department of the Army, 1975; Tilton, 1979), or if an individual suffers from aphakia (absence of the lens of the eye) (Colditz, 2015).

Sources and origin mechanisms of color (light).

Since color from the physics perspective is an attribute of visible light, in order to discuss how color(s) “originates” and is perceived, it is necessary to investigate the various sources and origin mechanisms of light (i.e., EM waves).

Light (color) sources.

Sources of visible light can be categorized via several schemes. In one approach, sources are classified as either *natural* or *artificial*. Natural sources include stars (e.g., the Sun), fires (from wood, grass, and other combustible material), atmospheric electrical phenomena, comets, and a number of biological sources (via bioluminescence),⁵⁰ e.g., fireflies and some species of

⁴⁸ Using 8 bits per color channel (see *Digital color* section).

⁴⁹ The term *laser* refers to the acronym, LASER, for Light Amplification by the Stimulated Emission of Radiation. The wavelength(s) of light emitted by a laser depends upon the material from which the laser crystal or gas is composed.

⁵⁰ *Bioluminescence* is the production of light by a living organism.

bacteria, fungi, and marine animals. Atmospheric electrical phenomena include meteorological lightning, auroras, Saint Elmo's fire,⁵¹ volcanoes, and meteors.

Atmospheric lightning, which ionizes the gases and heats them to incandescence as it passes through open air, emits white light; however, local atmospheric conditions can result in its appearance as different colors. For example, distant lightning can appear red or orange due to water vapor, haze, and dust in the lower levels of the atmosphere (Uman, 2012).

Volcanic eruptions produce molten rock (lava). The color of lava depends on the temperature, the chemical composition, and any impurities that are in the liquid rock. Colors can include orange, green, red, gray, brown, tan, silver, pink, and black. At its initial hottest temperature, it may glow a bright orange (1000-1150 °C); cooling to bright red (800-1000 °C), then dark red (650-800 °C), and brownish red (500-650 °C). Solid lava appears black (but can still be very hot) (Department of Geosciences at Oregon State University, 2015).

Examples of artificial sources include candles, gas burners, oil lamps, phosphor⁵² screens, fluorescent lamps, incandescent bulbs, fireworks (pyrotechnics), light-emitting diodes (LEDs), electric arc lamps, gas discharge tubes (e.g., neon and mercury-vapor lamps), and lasers.

Origin mechanisms of color.

Whether natural or artificial, sources are not simple entities that glow in the visible spectrum. Instead they are complex systems that have sophisticated underlying mechanisms that produce the emitted EM energy (light) interpreted by the brain as color(s). These color origin mechanisms are varied in their nature and are difficult to categorize using any definitive classification. In addition, color is not perceived in most situations from light directly emitted by a source but instead from light reflected by or transmitted by objects illuminated by a source.

Nassau proposed one classification system in which he identified 15 mechanisms⁵³ that give rise to spectral energy distributions that result in the perception of color(s) (Table 2) (1983).⁵⁴ He organized these mechanisms into five major groups:

- I. Vibrations and simple excitations
- II. Transitions evolving Ligand field effects⁵⁵
- III. Transitions between molecular orbitals
- IV. Transitions involving energy levels
- V. Geometrical and physical optics effects.

The first four groups involve the *emission* of EM energy (light). The last group (V) involves the *interactions* of light with natural and artificial materials; these interactions obey the

⁵¹ *St. Elmo's Fire* is a weather-related electrical phenomena predominately observed at the tips of pointed objects. It has been well documented for centuries by sailors who observed it at the tops of sailing masts. It is a corona discharge (ionization) that occurs during thunderstorms.

⁵² Phosphors are synthetic fluorescent or phosphorescent substances, best known for their use as coatings on the screens of cathode ray tubes.

⁵³ These mechanisms are described in greater detail in Steven Shevell's book, *The Science of Color*, published in 2003 by Elsevier Ltd., Oxford, UK; as well as Rolf Kuehni's book, *Color: An introduction to practice and principles*, published in 2013 by John Wiley & Sons, Hoboken, NJ.

⁵⁴ This list excludes any color experiences resulting from direct electrical stimulation of the brain.

⁵⁵ The Ligand field theory, attributed to the physicist J. H. van Vleck, describes the electronic complex compounds that consist of a central metal atom surrounded by a group of electron-rich atoms or molecules called *ligands* (Muller, 2007).

laws of geometrical and physical optics. One of the most common examples in this group is the blue color of the sky caused by the scattering of sunlight by the molecules of the atmosphere. This scattering, called Rayleigh scattering, is more effective at shorter wavelengths or blue portion of the visible spectrum. Other examples of this group include the colors present in butterfly wings, oil films, soap bubbles and rainbows, which generally are the result of the refraction, diffraction and interference of light.

Table 2. Classification of causes of color (adapted from Nassau, 1983).

I. Vibrations and simple excitations	
1. Incandescence	Flames (wood, candle, gas), tungsten lamps, the Sun, lightning
2. Gas excitations	Gas discharge/vapor lamps (neon, sodium, mercury), some lightning, auroras
3. Vibrations and rotations	Water, ice, Halogen vapors (iodine, bromine, chlorine)
II. Transitions involving Ligand field effects	
4. Transition metal compounds	Turquoise, lasers, many pigments, phosphors
5. Transition metal impurities	Ruby, emerald, some fluorescence, lasers
III. Transitions between molecular orbitals	
6. Organic compounds	Most dyes, most biological colors, some fluorescence, lasers
7. Charge transfer	Many pigments, blue sapphire, magnetite
IV. Transitions involving energy bands	
8. Metals	Copper, silver, gold, brass, “ruby” glass
9. Pure semiconductors	Silicon, galena, diamond
10. Doped or activated semiconductors	LEDs, some lasers and phosphors
11. Color centers	Amethyst, smoky quartz, some lasers and phosphors
V. Geometrical and physical optics	
12. Dispersion refraction; polarization	Rainbows, halos, sun dogs*
13. Scattering	Blue sky, red sunset; Raman, Mie and Rayleigh scattering
14. Interference	Soap bubbles, oil slick on water, some biological colors
15. Diffraction	Diffraction gratings, opal, some biological colors, most liquid crystals

*Sun dogs are an atmospheric phenomenon that consists of a pair of bright spots on either side of the Sun.

With the exception of group V, these classifications are somewhat subjective and subject to overlap. For example, lasers and fluorescent sources can emit light via multiple mechanisms in Table 2.

It is not necessary here to delve too deeply into the complex details of the various mechanisms. What is more worthwhile is to explore briefly examples of the *results* of a few of these mechanisms. These results are defined as the spectral energy distributions that arrive at the eyes and initiate the color vision process. The two most common mechanisms are heated solids (incandescence) and gas excitation.

Incandescence.

Incandescence is perhaps the best known and most frequently encountered color-causing mechanism and is an example of the conversion of thermal energy into EM energy. Incandescence is defined as the emission of *visible* light from a substance or object as a result of heating it to a high temperature. To emit visible light, a material must be heated to a temperature of at least 850 degrees Kelvin ($^{\circ}\text{K}$) (577 degrees Celsius [$^{\circ}\text{C}$]). The heating increases the kinetic energy of the affected atoms and molecules, which are composed of charged protons and electrons. This results in charge acceleration, the fundamental source of EM production, and photons (visible light) are emitted in the process. Energy emitted by a heated body consists of a wide range of frequencies and produces a continuous spectrum (i.e., energy is present at all wavelengths). Incandescence is not an efficient source of visible light, as much of the energy produced is in IR (heat) energy, e.g., ~98% of energy output from an incandescent bulb is heat.

Three well-known incandescent sources are the Sun, a candle flame, and a tungsten bulb. The Sun (Figure 6, left) is a gigantic ball of incandescent gas. The portion of the Sun visible is the photosphere. Sunlight is the incandescence of this hot surface of the Sun. Its spectral energy distribution across the visible portion of the spectrum is continuous. Although the peak of the solar spectrum is at approximately 470 nm (blue-greenish), the Earth's atmosphere absorbs and scatters much of the blue light, making the Sun appear yellowish-white in color. It is this light, reflecting off the objects in our environment, that makes the world visible.

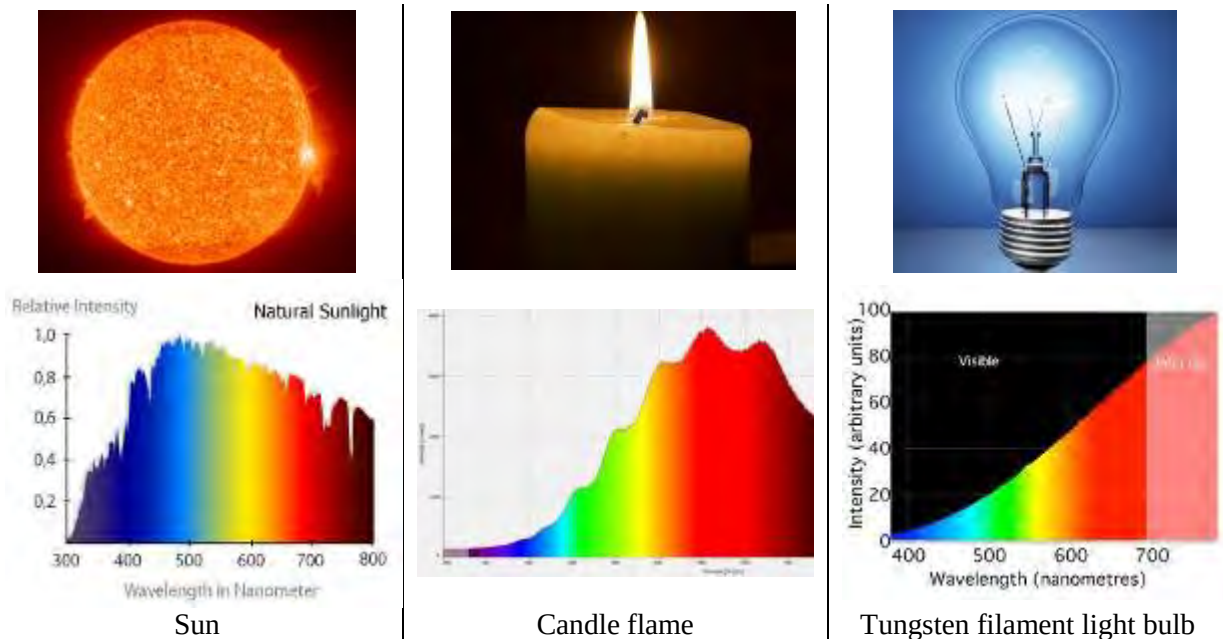


Figure 6. Spectral energy distributions for three examples of incandescent light sources: the Sun (left), a candle flame (middle), and a tungsten filament light bulb (right).

In combustion flames (fires), chemical reactions release heat, releasing gases and raising materials to temperatures at which the combustible materials and the resulting gases

incandesce.⁵⁶ The color of a flame depends on a variety of factors. The temperature, the fuel's chemical composition, and the amount of oxygen present determine the color of the flame. Most wood fires are a bright orange due to the presence of sodium, which emits strongly in the orange portion of the visible spectrum. The blue in wood flames comes from carbon and hydrogen, which emit in the blue and violet. Copper compounds emit in the green or blue; lithium produces a red emission.

Candles are an interesting light source in the method by which the combustion occurs. A candle typically consists of a braided cotton wick encased in wax. Wax is essentially hydrocarbons, being mainly composed of hydrogen and carbon atoms (National Candle Association, 2015). When a candle is lit, the heat of the flame melts the wax near the wick, and the liquid wax is drawn up the wick by capillary action (Figure 6, middle). The flame's heat vaporizes the liquid wax, breaking down the hydrocarbons into molecules of hydrogen and carbon. These vaporized molecules are drawn up into the flame, where they react with oxygen from the air to create heat, light, water vapor, and carbon dioxide gas. Enough heat is created to melt more wax to keep the combustion process going until the fuel is used up or the heat is eliminated. The colors of candle flames occur in zones. The area at the bottom of the flame has a bluish color; above is a smaller dark orange-brown section; and at the top is a large yellow region. The spectral output of a candle is continuous, and, in general, is assigned a yellowish color.

A light bulb (Figure 6, right) uses electrical current conducting through a thin wire (or filament) to heat the wire to a high temperature, causing it to incandesce. In many incandescent lamps, the filament is made of tungsten, a special metal that can stay at a high temperature for over a hundred hours without melting. The filament is enclosed in a glass bulb usually filled with an inert gas (typically argon) to prevent oxidation that would result in rapid failure of the filament. Since only the small central filament incandesces, the bulb is frequently made of frosted glass in order to produce more uniform illumination. The spectral output of a tungsten light bulb is continuous, with only a small portion of its output (~10%) in the visible region. Typically, its output is perceived as reddish-yellow in color.

Since incandescence produces a continuous spectrum referred to as “white” light, energy distributions that can be perceived as different colors can only be obtained via the use of filters. These filters absorb some wavelengths and transmit the rest. For example, if white light is viewed through a green filter, energy at all wavelengths other than a selective group in the green will be absorbed and only green light will be perceived. This technique is called color by *subtraction* or *subtractive* color (see *Color Science* section). It is obvious that this is a very energy-inefficient technique for achieving color.

Gas discharge.

After incandescent sources, the most common sources are those based on the mechanism of gas excitation (or gas discharge). A gas discharge tube is typically a glass tube with two electrodes and containing a gas or gas mixture. The tubes have the property that, as the voltage

⁵⁶ *Combustion* is a chemical reaction in which fuels react with an oxidant compound, usually oxygen (O₂). As it is an exothermic reaction, the process releases heat; visible light energy also is produced. The most common fuels include natural gas, oil, and wood.

applied across the electrodes is increased, a point called the “breakdown voltage” is reached where any localized ionization of the gas will initiate an avalanche process that spreads through the tube. The color of the light from the lamp varies with the gas or gas mixture. Each gas emits certain wavelengths depending on its atomic structure. In contrast to incandescent sources, which emit continuous spectra, gas discharge sources emit EM energy at specific wavelengths. The resulting spectra are called line spectra (Figure 7, bottom, right). Two examples of gas discharge sources include the pervasive fluorescent⁵⁷ tube and neon signs (Figure 7, top).

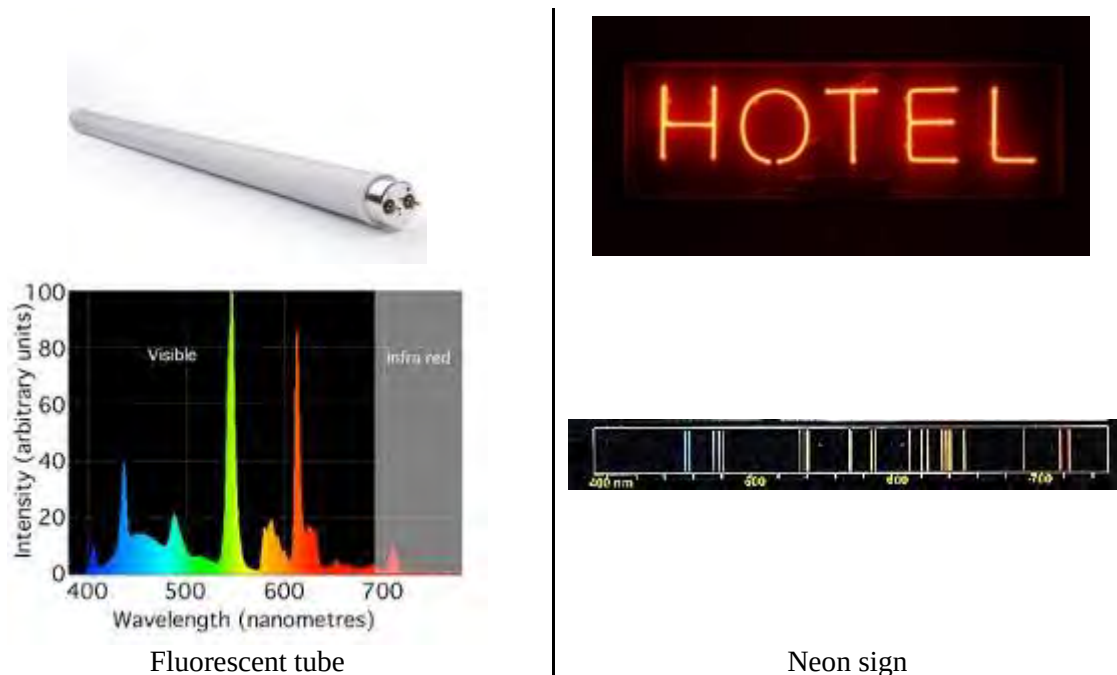


Figure 7. Spectral energy distributions for two examples of gas excitation light sources: fluorescent tube (left) and neon sign (right).

Neon lights were named for the noble gas neon, which gives off a red-orange light. However, the generic use of “neon” signs frequently refers to lights that contain other gases, making available a multitude of colors. The color of the light depends on the gas in the tube. These gases (and their resulting color) include: argon (violet), carbon dioxide (white), hydrogen (red), helium (yellow), mercury (blue), and sodium (bright orange-yellow). The narrow visible line spectra of a true neon sign is shown in Figure 7 (right). The first line is at approximately 540 nm (green); yellow, orange, red-orange, and red lines also are present, with the highest visible line at approximately 703 nm (red), which is perceived as orange by the human visual system.

Fluorescent lamps are a large category of light sources. They have been the workhorse of commercial and industrial lighting for decades. The most common type of fluorescent lamps is the hot cathode lamp. This lamp consists of a glass tube filled with an inert gas (usually argon) with a small amount of mercury at low pressure. A tungsten electrode is located on each end of the tube. When voltage is applied, free electrons flow (arc) from one electrode to the other. As

⁵⁷ Fluorescence is defined as the emission of visible light as the result of bombardment by other kinds of EM radiation, such as X-rays or UV light.

electrons move through the tube, most collide with the gaseous mercury atoms. These collisions excite the atoms, raising electrons up to higher energy levels. When the electrons spontaneously return to their original energy level, they release photons. In mercury atoms the photons are in the UV wavelength range. The human visual system does not respond to UV energy, so the inside of the lamp is coated with phosphors that do emit energy in the visible spectrum. When the UV photons hit the phosphor atoms, the phosphor's electrons are raised to a higher energy level. When these electrons return to their normal level, energy is released in the form of visible photons. The spectrum of a representative fluorescent light bulb is shown in Figure 7 (left). Note there have intense emission lines at several wavelengths from the mercury vapors, with a continuous background as the result of the phosphors in the tube; the perceived color is white.

LED and laser sources.

Two additional and rather prominent light sources deserve discussion, especially with their distinctive color capabilities; these are the LED and the laser (Figure 8). In Nassau's color-causing classification scheme, LEDs are an example of doped or activated semiconductors in the group *Transitions involving energy bands* (1983). Lasers are diverse in their color-causing mechanism classification, which is dependent on the lasing medium (e.g., gas, dye, and solid semiconductor).

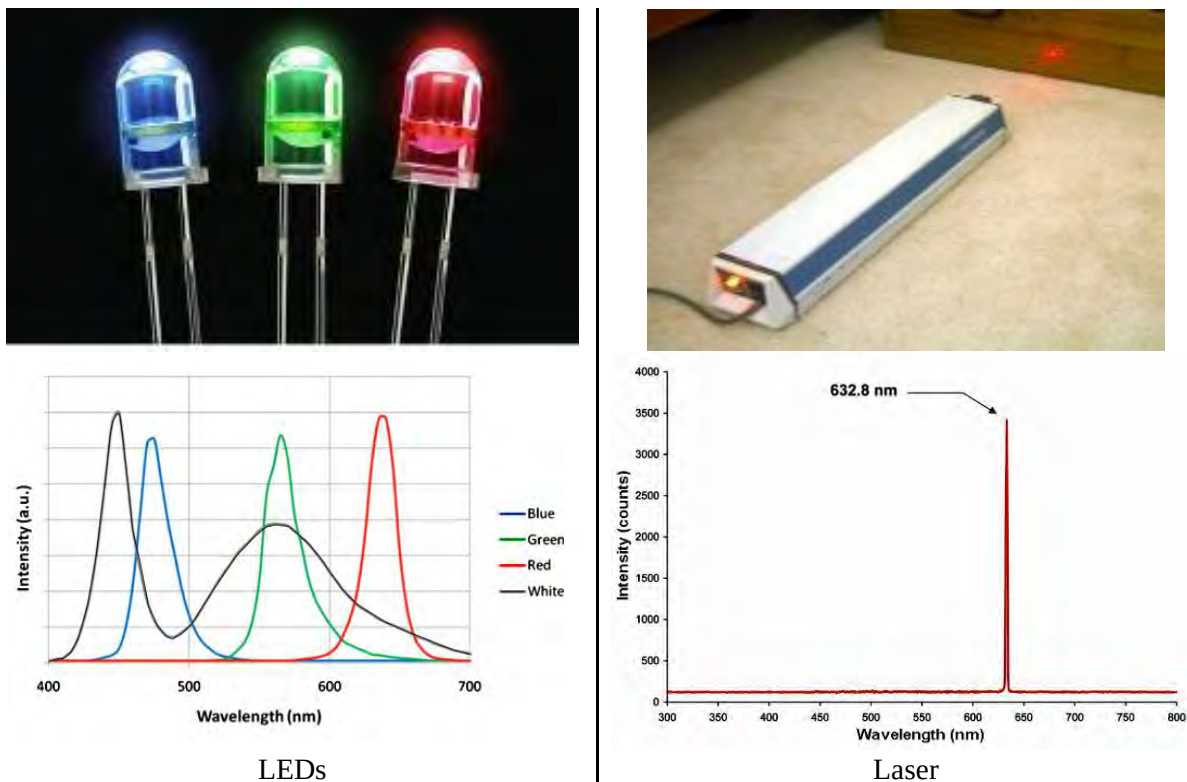


Figure 8. Spectral energy distributions for LEDS and a laser.

LEDs.

LEDs, also referred to as solid-state lighting, have a number of advantages over incandescent, fluorescent, and other light sources (Stafford, 2010; Whitaker, 2005). These include:

- High longevity – Lifetime up to 100,000 hours, with 60,000 hours more typical; however, performance may degrade depending on operating current and temperature
- Small form factor
- High efficiency – 80-90%, compared to 20% for conventional incandescent light bulbs
- Low power consumption
- Wide temperature range – In general, the colder the environment, the higher the light output will be; higher temperatures reduce light output
- Dimmable
- Directional – Light is originally emitted in all directions; however, most LEDs emit light preferentially in one direction (often via built-in reflecting cavity) (Figure 9)
- Durable – Encapsulated in an epoxy resin, with no filament or gas
- Minimum IR (heat) and UV radiation – However, heat sinking make be required as heat is produced at the semiconductor junction
- Color availability – Available in a wide range of colors, which include red, amber, green, blue, and white; can be combined together to produce millions of color options

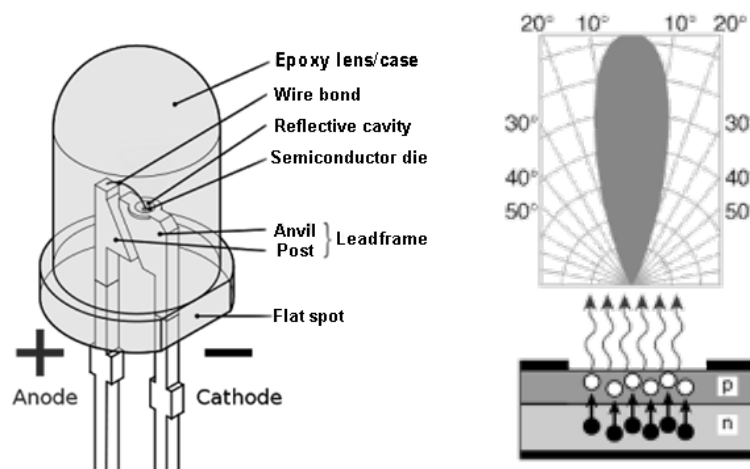


Figure 9. Many LED light sources are directional in their output, often via a reflective cavity.

With these operational advantages, LED lamps have virtually replaced miniature incandescent lamps as indicator lights. However, larger LED bulbs have been slow to be accepted as replacements for conventional light bulbs due to cost. A typical 60-Watt incandescent bulb costs \$0.50, while its LED equivalent costs approximately \$15-\$20, although is rapidly decreasing (Curran, 2015).

As a semiconductor device, LEDs are based on the nature of the junction between two types of materials identified as n- and p-type. These distinct materials are produced by adding impurities to pure semiconductor material, a process called *doping*. It is this doping that will determine the method by which current is carried. In an n-type material, current is carried by electrons; in a p-type material, current is carried by holes (regions of the material that lack an electron; a vacancy). An important property of a p-n semiconductor junction is electric current can flow more easily in one direction than in the other. It is at this p-n junction where the light is created and emitted as photons (a process known as electroluminescence) (Figure 10). This occurs when electrons at a higher energy level “drop down into” holes at a lower energy level. The wavelength of these photons (and hence the color) is directly proportional to the difference in the energy levels (Beiser, 1992), which is determined by the type and proportion of the doping impurities (Sinclair & Dunton, 2007).^{58,59}

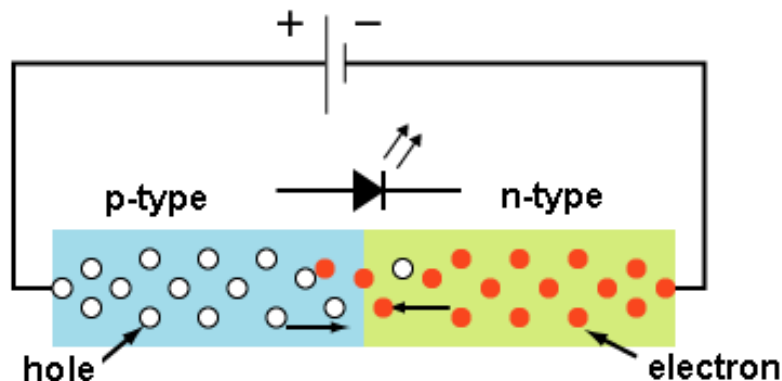


Figure 10. Diagram of p-n semiconductor junction. Photons are emitted when a voltage is applied.

It is important to note that LEDs produce color directly. LEDs are inherently more efficient due to the light-producing solid-state mechanism. Their efficiency is further enhanced because their output does not have to be additionally filtered, as do incandescent sources, in order to achieve a desired color. For example, if green light is desired, the LED can be doped with the proper impurities to create low energy levels (holes) suitable for emission at the desired green wavelength (Curran, 2015).

The early history of the discovery of the basic principles of the LED is not well established. However, it is well documented that the first visible LED (red) was developed in 1962 at General Electric, Syracuse, NY, by N. Holonyack, Jr., based on work in the late 1950s. However, as early as 1907, Henry J. Round, who worked at the Marconi Labs, London, published a short description of the process called electroluminescence when he observed the presence of visible light after applying voltage to crystals of raw silicon carbide (carborundum) (Zheludev, 2007).⁶⁰ The 1970s saw the spectral output of LEDs expand to include yellow, green, and violet. However, it was two decades later, in 1992, that the first blue LED was developed by

⁵⁸ For example, combining varying proportions of gallium arsenide (GaAs) with gallium phosphide (GaP) can produce LEDs that emit light from 580 nm (yellow) to 690 nm (red).

⁵⁹ The semiconductor material determines the color of the LED emission, not the color of packaging envelope. LEDs of all colors are available in clear or diffused (milky) packaging.

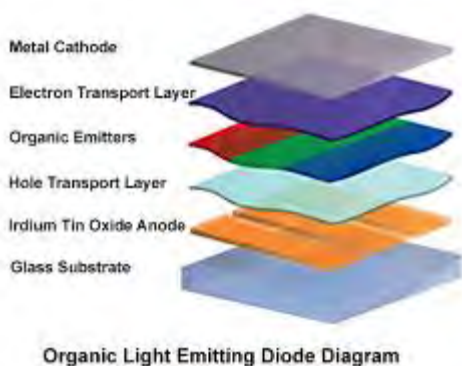
⁶⁰ In the 1920s, the Russian researcher, Oleg V. Losev, published a number of papers reporting the same phenomenon in SiC, but his work did not become known outside Russia until the 1950s.

Japanese researcher S. Nakamura.⁶¹ The invention of the blue LED finally enabled the development of LEDs that appear white. By collocating red, green, and blue LEDs into one envelope, and properly mixing the amount of their output (Zhao, Narendran, & Derlofske, 2002), the resulting light appears white. An alternative method for constructing a white LED uses a violet or UV LED to provide energy that then excites a secondary phosphor to emit full-spectrum white light (Spring, Fellers, & Davidson, 2015).

Bi-color LEDs are available where either of the two colors can be selected for emission (but not simultaneously). This is achieved by mounting two LEDs in “inverse parallel (one forwards, one backwards)” inside a single envelope.

The spectral distributions for representative red, green, blue, and white LEDs are presented in Figure 8 (left, p. 22). With the obvious exception of white, LEDs frequently are described as being monochromatic in their spectral output. However, LEDs actually emit light in a narrow band of wavelengths, giving the appearance of a nearly monochromatic source. Full width at half maximum (FWHM)⁶² is typically 40-70 nm.

One of the more intriguing and recent additions to the family of LEDs (at least in terms of manufacturing maturity), and most promising for display technologies, is the *organic* LED (OLED). OLEDs are a type of LEDs where the emissive electroluminescent layer is composed of thin films of organic molecules. Light is produced by applying a voltage to two thin organic film layers sandwiched between two conductors (Figure 11, left) (Chang, 2013). Displays composed of OLEDs share most of the advantages of all LED displays, e.g., high efficiency, low power consumption, wide color range). They also offer increased brightness, higher contrast ratios, wider viewing angles, deeper blacks, and more vibrant colors than previous LED types. In addition, OLED displays can be made flexible (even rollable) and transparent, very desirable characteristics for displays used in mobile devices (Figure 11, right).



Layered structure of an OLED



Flexible and transparent OLED display

Figure 11. Layered structure of the OLED (left) and the flexible and transparent properties of an OLED display (right).

⁶¹ Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura were awarded the Nobel Prize in physics in 2014 for their work on the blue LED.

⁶² *Full width at half maximum* (FWHM) is an expression of the extent of a function given by the distance between points on the curve at which the function reaches half its maximum value.

It should not be surprising that the number of applications for LED light sources abound. Almost anywhere an incandescent source is used, an LED can replace it at greater efficiency. Fields of applications include: signs, architectural lighting, signals (e.g., auto, railway, aviation), and mobile electronics (e.g., laptop computer, mobile phone, and digital camera displays). The durability and long lifetime of LEDs make them an optimal choice for exposed or difficult-to-access lighting. The enhanced physical and performance properties of the OLED make this technology an optimal prospect for both panel-mounted and head-mounted display HMD aviation applications.

Lasers.

Lasers are sources producing high intensity beams of light that are monochromatic⁶³ (high color purity), coherent, and highly collimated (low divergence). While lasers can emit energy across much of the EM spectrum (near X-rays to far-IR), the color of a laser is associated only with wavelengths in the visible portion of the spectrum, i.e., the wavelengths to which the eyes are responsive.

Laser emission follows the laws of quantum mechanics, which limit the stored energy of atoms or molecules to discrete quantities. In previous discussions of other light production (color source) mechanisms, a process was introduced where electrons in lower energy levels gain energy (e.g., via heat), transition to higher energy states, and then spontaneously transition back to their initial (lower) states, emitting photons having energy equal to the difference between the two energy levels. This process is known as *spontaneous* emission. Laser energy is the result of a different process, *stimulated* emission. Indeed, as stated previously, the term LASER is an acronym for (L)ight (A)mplification by (S)timulated (E)mission of (R)adiation (Gould, 1959). In the laser process, a condition known as population inversion (more electrons in higher energy states than lower ones) is created by adding energy to the laser medium; the first laser used a method of producing a population inversion known as optical pumping.⁶⁴ The lasing action occurs when a spontaneously emitted photon stimulates further emissions, generating a cascade of photons; this is the amplification part of the process (Beiser, 1992).

It is generally cited the first laser was demonstrated in May 1960 using a crystal of a synthetic ruby excited by a flash lamp (Hecht, 2015).⁶⁵ This laser produced visible light at a wavelength of 694.3 nm (red). A few months later in December 1960, the first *gas* laser was demonstrated using a mixture of helium and neon gases; energy was emitted at a wavelength of 632.8 nm (red) (Figure 8, right). This He-Ne laser, as it was called, was the first laser to have wide commercial use and eventually could be found in every high school and college physics laboratory. In September 1962, the first *semiconductor* laser was operated. Also known as a laser diode or injection laser, its active laser medium consisted of a p-n junction of a semiconductor diode similar to that found in a LED.

⁶³ The emission of a laser is usually the result of *one* atomic transition that has a single exact wavelength, making the laser *one* spectral color and the most monochromatic light source obtainable.

⁶⁴ Chemical reactions, electrical discharges and current, laser diodes, and other lasers are additional pumping methods to create population inversions.

⁶⁵ It is actually Chromium ions in the ruby crystal that are excited.

Today, there are thousands of types of lasers using a wide array of lasing media, typically grouped as solids, liquids and gases. While, as previously stated, as a group, lasers can produce EM energy across a wide portion of the EM spectrum, only laser types that emit energy at the wavelengths in the visible spectrum produce the perception of color. The range of colors (wavelengths) is quite vast and includes almost all possible colors: red, orange, yellow, green, blue, and blue-violet. In 2015, researchers at Arizona State University, Tempe, Arizona, announced that the creation of the first “white” lasers that emit energy over the full visible spectrum via a monolithic structure capable of emitting red, green, and blue light simultaneously (Choi, 2015; Fan, Turkdogan, Liu, Shelhammer, & Ning, 2015).

Summary of light sources.

A summary of the most common sources of color (light) identifying source type (natural vs. artificial), source mechanism, and most frequently associated color(s) is presented in Table 3.

Table 3. Summary of light sources.

Light (color source)	Source type	Source mechanism	Typical colors
Sun	Natural	Incandescence	Yellowish-white
Fire	Natural	Incandescence	Orange, blue, red, yellow
Volcano lava	Natural	Incandescence	Orange, red, green, brown, black
Meteorological lightning	Natural	Incandescence due to electrostatic discharge; gas excitation	White, red, orange
St. Elmo’s Fire	Natural	Gas excitation	Blue
Tungsten filament bulb	Artificial	Incandescence	Yellowish-orange
Light-emitting diodes (LEDs)	Artificial	Spontaneous emission	Red, amber, yellow, green, white
Lasers	Artificial	Stimulated emission	Red, orange, yellow, green, blue, blue-violet, white
Neon-filled tube	Artificial	Gas excitation	Red-orange
Argon-filled tube	Artificial	Gas excitation	Violet
Zenon-filled tube	Artificial	Gas excitation	Orange
Sodium vapor lamp	Artificial	Gas excitation	Bright orange-yellow
Fluorescent (Mercury vapor) tube	Artificial	Gas excitation	White

Putting light sources to work in displays.

Over the developmental history of the aviation crew station, an ever-growing array of these light sources has been used in cockpit displays. When manned powered flight began with the Wright brothers in December 1903, flight was a daytime venture. There were no lights in the cockpit to illuminate the rudimentary flight instruments. Only after pilots began routinely flying aircraft at night – as a result of the U.S. Post Office’s decision in the 1920s to use airplanes for mail delivery – was there recognition of the need for cockpit lighting (Patzner, 1996; Rash &

Manning, 2003). The first attempts at cockpit illumination involved lights that were removed from farm tractors and mounted in the open cockpits of the biplanes that carried the U.S. mail.⁶⁶ The first significant lighting system consisted of UV light used on the indicia (e.g., legends and characters) of the needles on dials that were painted with luminescent paint (NAJACO Publishing, 2003); the UV light caused the indicia to glow. This use of UV light was common before and during World War II (WWII) (Figure 12). (Note: See additional discussions of cockpit lighting in *Interior lighting* and *Color in aviation charts and maps* sections.) During the 1950s, UV lights were replaced with lamps known as “post lights” that were mounted on the instrument panel (Figure 13).⁶⁷ Each post light consisted of an incandescent lamp inside a small cylindrical



Figure 12. WWII era display with UV light illuminated indicia (left) and the displays installed in a P-38 cockpit (right).



Figure 13. Post light showing an incandescent bulb mounted in a cylinder.⁶⁸

tube with a cap; a slit in the tube allowed light to illuminate the dials. A major problem with post lights was (and in some older aircraft still is) the non-uniform lighting of instruments. The brightness of post lights was controlled by a rheostat, which had to provide a relatively high

⁶⁶ These lights were powered by automobile batteries that were removed periodically from the aircraft for recharging.

⁶⁷ The post light design is attributed to Warren G. Grimes, a pioneer in aviation lighting. Grimes designed the interior lighting for the Ford Trimotor aircraft for the Ford Motor Company. In 1933, he started Grimes Manufacturing Company, later Grimes Aerospace Company, which as of 1997 operates as a subsidiary of Honeywell International, Inc.

⁶⁸ This installation approach was subject to bulb failures, sometimes requiring pilots to have to pirate a post light from a less important instrument during flight.

setting in order to see all the information on the dial.⁶⁹ Therefore, dimming the lights in darkness requires some compromises in order to reduce glare on the canopy or windshield. During the 1960s and 1970s, full instrument panels were introduced, and color was added for warning lights and caution lights. Color for individual lights was achieved via color filters.

In response to the crowding of the instrument panel as more and more instruments were added, a new concept of crew station displays was introduced using a display that produced its own lighting rather than requiring illumination by a separate light source. This display was the cathode ray tube (CRT), a vacuum tube in which a beam of electrons is projected onto a phosphorescent screen to produce a luminous spot at a varying point on the front of the display. Initially, inadequate contrast and poor readability were problems during day operations, even when hoods were used to prevent direct sunlight from striking the CRTs. Advances in narrow-band phosphors in the early 1970s finally made CRTs acceptable cockpit displays.

In the 1980s, CRTs began to be replaced by liquid crystal displays (LCDs), which consist of a matrix array of picture elements (or pixels)⁷⁰ of a liquid crystal material⁷¹ that act as small shutters. LCDs are non-emissive displays and operate on either passive or active technologies, with active-matrix LCDs (AMLCDs) being more employed in high quality displays. Regardless of technology, LCDs produce images by modulating light, which can be either reflected light or transmitted light from a secondary, external source (e.g., a backlight). Reflective LCD displays operate without the use of a backlight, relying instead on ambient light. Without the need for a backlight, this type of LCD is less expensive. Reflective LCDs have excellent readability in sunlight or lamplight but are useless if no ambient light is available. While reflective LCDs traditionally are considered as B/W displays, researchers have developed low-power reflective displays with a wide color gamut (range of colors). This is achieved using achromatic polarizers and anisotropic diffusion layers. The display requires the chromaticity of optical components be suppressed using a technique by which the optical diffusion of reflected light is controlled. The display is reported to have a wide color gamut and high reflectivity, making it optically similar to white paper (Ishinabe, Miyashita, & Uchida, 2012; Ishinabe & Uchida, 2008).

In transmissive LCDs, the LC segments either block or transmit light from a backlight source, which can be located on the side or back of the display panel. A variety of light sources have been employed for backlighting: incandescent lamps, electroluminescent panels, cold cathode fluorescent lamps (CCFLs), and LEDs. Some LED backlighting used blue LEDs with yellow phosphors to produce white light. As a result, considerably more blue light was present than red or green, sometimes resulting in inaccurate color presentations. In addition, some backlights were edge-mounted (prompting the term “edge-lit”) and required a diffuser to provide quasi-uniform backlighting illumination. As technology improved, electroluminescent or full array LED panels (with red, green, and blue LEDs) were used to provide uniform lighting over the entire display with better color accuracy.

Generally, modern cockpit lighting making use of these technologies provides far better illumination under most daylight and night conditions than the older flood/post light systems. In

⁶⁹ Instrument panel floodlights also were used for preflight and post-flight checks as backup lights in case of a primary lighting system failure, and as an adjunct to the primary lighting system.

⁷⁰ The term *pixel* is a contraction of the words “picture element,” and is defined as a small area of illumination on a display.

⁷¹ Liquid crystal is a state of matter intermediate between solid and amorphous liquid.

addition, where the older lighting systems basically provided the same illumination level across the full instrument panel, modern cockpits provide greater flexibility, which is important in multi-crew aircraft. The pilot and co-pilot can adjust their individual display lighting to satisfy their visibility requirements; settings of shared displays in the center of the instrument panel usually are a compromise.

Although liquid crystals were first discovered in 1888, it was not until the 1960s that researchers at the RCA David Sarnoff Research Center in Princeton, New Jersey, demonstrated the first display based on this technology (Kawamoto, 2002). Full-color LCDs were demonstrated in the late 1980s (Hotta et al., 1986; Nagayasu et al., 1988), Manufacturing reliability problems slowed large scale production, and it would be four decades, in the 2000s, before LCDs finally overtook CRTs in performance and reliability. Currently, LCDs are the leading display technology, although OLED displays are becoming increasingly competitive (Templier, 2014).

In military aviation, the AMLCD has become the preferred flight instrument technology since the late 1990s, being employed in both fixed- and rotary-wing aircraft (Snow, Jackson, Meyer, Reising, & Hopper, 1999). Increasingly larger AMLCDs are significantly increasing information capacity, providing both sensor and flight data fusion into the cockpit. This enhances pilot situation awareness and efficiency.

Achieving color in displays.

For small filament incandescent indicator lamps, such as employed in aviation instrument panels, color was, and still is, achieved via the use of color filters or color-filtering glass envelopes (Figure 14, top, left). Incandescent lamps are broad spectrum, and the filter absorbs the unwanted wavelengths, allowing the desired color to be transmitted. A wide range of colors are possible. The outputs of these color-filtered lamps appear highly saturated. However, they are not very monochromatic, still having a fairly wide band of wavelengths. They can even have small amounts of energy at a different color (Gordon, 2011).

In a CRT, light is emitted when an electron beam strikes a phosphor coating on the front inside of the tube. In a black-and-white CRT, there is *one* phosphor (or phosphor mixture)⁷² that emits white light when excited by the electron beam. In a color CRT, *three* electron beams strike *three* different phosphors arrayed as dots or stripes that emit red, green and blue light (Figure 14, top, right). In general phosphors are characterized by their emission spectra color and persistence, the length of time after excitation that they continue to emit light (persistence). There are a number of phosphor formulations that have emission spectra with peak emittances and efficiencies in the red, green or blue. The choice of these phosphors determines the range of colors (color gamut)⁷³ that can be presented. As an analog system, a color CRT can theoretically present an infinite number of colors.

⁷² For example, a fine mixture of two phosphor powders, a yellow and a blue emitting, can provide a good approximation of white (Nassau, 1983).

⁷³ In color displays, the *color gamut* refers to the subset of colors that can be accurately presented on the display.

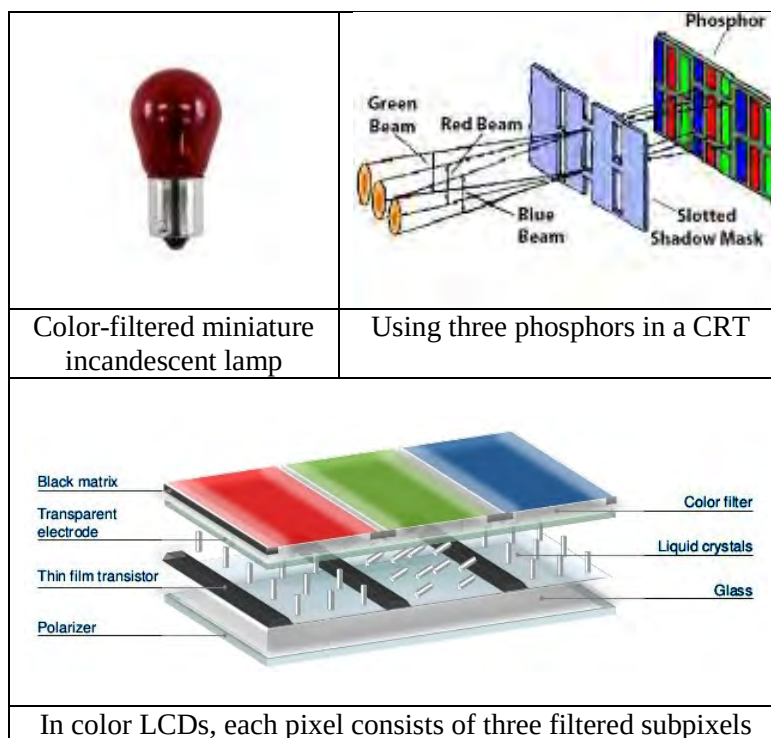


Figure 14. Achieving color in incandescent lamps (color filter), CRT displays (tri-phosphor pattern), and LCDs.

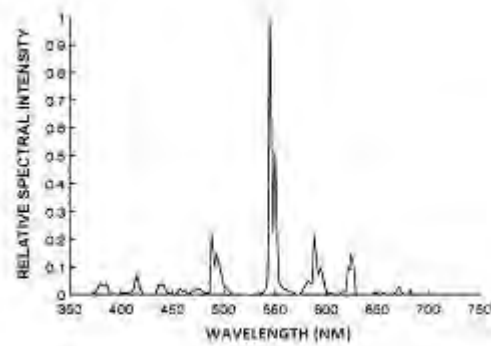
Although a worldwide phosphor identification system⁷⁴ was adopted in 1982 (Keller, 1983; Tannas, 1985), most phosphors in aviation use are best identified by the letter “P” followed by an identifying number (e.g., P-1, P-4, P-43). P-1 and P-4 are widely used white phosphors. P-43 is considered a monochromatic yellow-green phosphor with a peak emission at approximately 543 nm (Figure 15, right); it is used in the miniature (1-inch diameter) CRT (Figure 15, left) employed in the AH-64 Apache’s IHADSS HMD (Figure 1, bottom, right, p. 2) and in the U.S. Army’s ANVIS I² tubes.

In LCDs, backlights are available in many colors. Monochrome LCDs typically have yellow, green, blue, or white backlights. To produce “full” color, LCDs must use a full-spectrum (or white) backlight. Each “color” pixel consists of three subpixels using red, green, and blue color filters (Figure 14, bottom); these sub-pixels can take on a variety of patterns (Semenza, 2013). Through the control and variation of the applied voltage, the intensity of each subpixel can range over 256 levels. Combining the subpixels allows a possible palette of nearly 16.77 million colors (256 red x 256 green x 256 blue). Figure 16 shows a representative emission spectrum for a computer monitor displaying a white background.

⁷⁴ In April 1, 1982, the Worldwide Phosphor Type Designation System (WTDS) was adopted to replace existing phosphor designation systems in use in various countries (Keller, 1983).



Miniature P-43 based CRT used in IHADSS



Emission spectra for P-43 phosphor

Figure 15. Emission spectra (right) for the P-43 phosphor of the miniature CRT (left) used in the AH-64 Apache's IHADSS HMD.

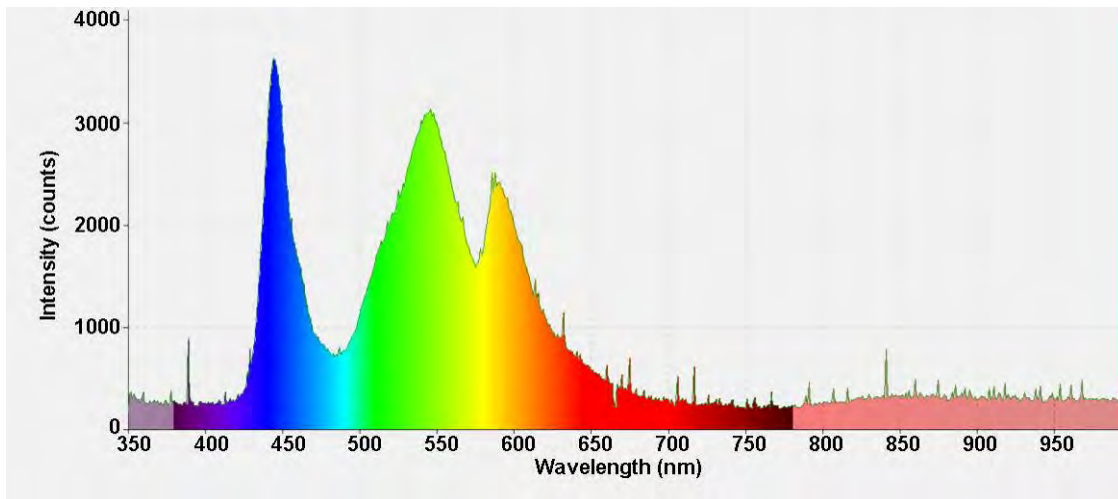


Figure 16. Example of an emission spectrum of a LCD monitor displaying a white screen.

Color temperature.

The commonly-used phrase “white hot” implies a relationship between color and temperature; this is because very hot objects are observed to glow (radiate light). Temperature is a measure of the internal energy of an object, i.e., the kinetic energy of constituent particles (atoms and molecules), and determines the perceived color of the emitted light.

Color temperature is a characteristic of visible light; it plays an important role in defining light sources across a multitude of applications, e.g., lighting, still and motion photography, publishing, manufacturing, and various scientific fields. The color temperature of a light source is the temperature of an ideal blackbody radiator that emits light of a comparable hue (color) to

that light source. The temperature is conventionally stated in units of absolute temperature, expressed in °K.⁷⁵ (See also *Color spaces and models* section.)

The Kelvin color temperature scale is based on a blackbody⁷⁶ object (e.g., a tungsten lamp filament) being heated. At some point the object will become hot enough to begin to glow (i.e., photon emission by thermal process). As it gets hotter, its glowing color will shift, moving from red (~900 °K), to orange, to yellow, and finally to white (bluish) hot (~10,000 °K). A temperature value of 798 °K (977 °F, 525 °C), known as the Draper point, is the temperature at which all solids begin to glow with a dim red color (Mahan, 2002). Light sources that glow this way are called "incandescent radiators" and emit a continuous spectrum. This means that they radiate light energy at all wavelengths of their spectrum. This spectrum will have a peak output at a frequency (or associated wavelength) that follows Wien's Displacement Law, which states the peak frequency is directly proportional to the absolute temperature: $f_{\text{Peak}} \propto T$. This peak frequency determines the dominant color of the light source. Figure 17 presents blackbody radiation curves for a range of color temperatures.⁷⁷

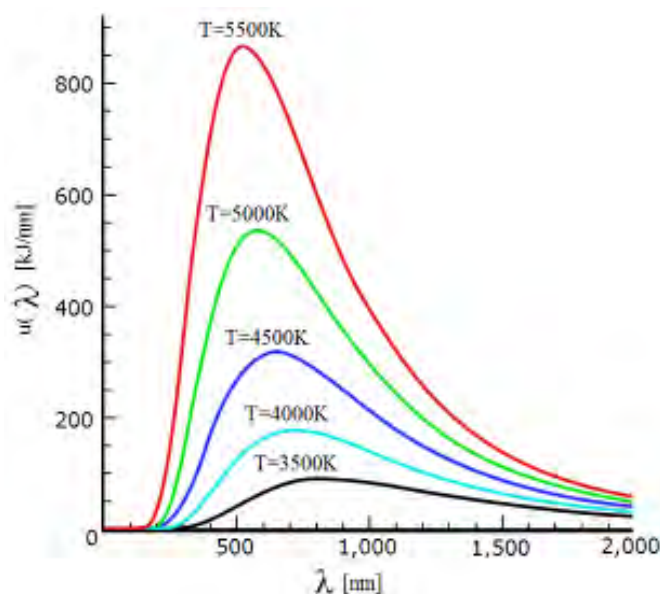


Figure 17. Blackbody radiation curves for selected color temperatures.

Only continuous sources meet the strictest definition of having a color temperature. Light sources that are not thermal (incandescent) radiators (but instead produce light by other mechanisms) have what is referred to as a "Correlated Color Temperature" (CCT). CCT extends the practice of using the Kelvin color temperature scale to specify the spectrum of light sources other than blackbody radiators (Grum, Saunders, & MacAdam, 1978). Incandescent lamps and day sunlight closely approximate the spectra of blackbody radiators at specific temperatures and can be designated by the corresponding temperature of a blackbody radiator (Robertson, 1968). For example, the emission spectra of fluorescent and LED sources, which differ substantially

⁷⁵ The Kelvin scale measures absolute temperature with 273 °K being equivalent to water's freezing point. A change of 1 °K is equivalent to a change of 1 degree Celsius (°C).

⁷⁶ A blackbody is a theoretically ideal radiator and absorber of EM radiation, regardless of frequency or angle of incidence.

⁷⁷ Note: The color of the curves in this diagram is not necessarily representative of the color of the object emitting that light.

from blackbody radiators in their methods of producing photons, can have a color appearance similar to a blackbody radiator of a particular temperature and be represented by a given CCT.

Figure 18 shows approximate CCT values of some common light sources, expressed in °K. Displays capable of presenting white light on the screen frequently are defined as having a color temperature. Most current computer monitors (and televisions) allow users to adjust the color temperature. As would be expected, reducing the color temperature on a monitor gives the entire screen an increasingly reddish cast; increasing the color temperature results in an increasingly bluish cast. The method for adjusting color temperature varies from product to product, sometimes asking users to choose from such terms as "blue" and "red," or "cool" and "warm"; other times requesting users to set a numerical color temperature value, e.g., 6800 °K or 9100 °K (Eizo, Inc., 2015). For most situations, the standardized color temperature for displays is 6500 °K, which approximates the color of outdoor lighting on a bright, sunny day. Monitors calibrated to a white point⁷⁸ of 5000 °K to 5500 °K tend to look too warm (yellow) and dingy (dark)

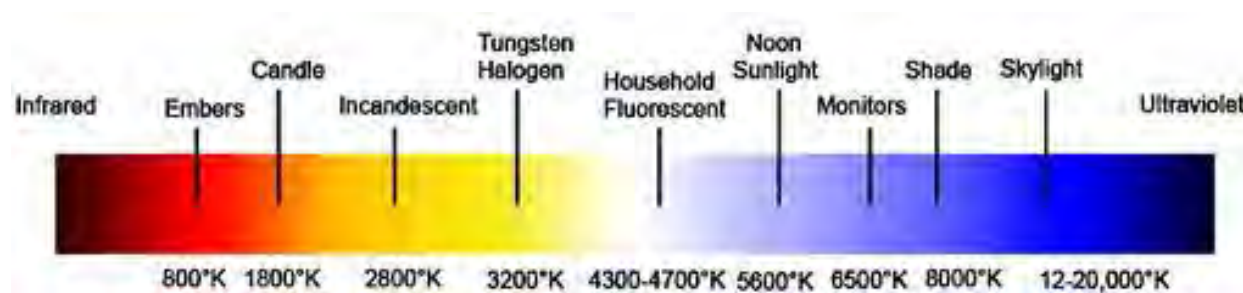


Figure 18. Color temperatures of common light sources, expressed in degrees Kelvin (°K).

Spectroradiometry.

While it is the human visual system that intrinsically captures and interprets the color of a given spectral distribution of light energy emitted, reflected or transmitted by an object, it is useful and frequently necessary to measure the total energy that reaches the eye, as well as the amount of energy present at each wavelength (or frequency).

Radiometry is the measurement of the total radiance of a light source (and its spatial and angular distributions); it is a single value, the sum of all energy over a specific range of wavelengths. In practice, radiometry usually is confined to the UV, visible, and IR wavelengths. Radiance is expressed as the total radiant intensity per unit projected area. The Standard International (SI) unit for radiance is the watt per square meter per steradian⁷⁹ (watt/m²-sr). The measurement instrument for radiance is the radiometer.

Closely related to radiometry is *photometry*, which is the measurement of light in units that are weighted according to the sensitivity of the human eye (i.e., only visible light energy). The photometric measure of the luminous (eye-weighted) intensity per unit area of light

⁷⁸ The *white point* is set of chromaticity coordinates that serves to define the color "white" in image capture, encoding, or reproduction (see *White and black points* section).

⁷⁹ The *steradian* (sr) is a unit of solid angle. There are 4π (approximately 12.5664) steradians in a complete sphere.

travelling in a given direction is known as luminance.⁸⁰ Luminance describes the amount of visible light that passes through, is emitted by, or reflected from a particular object or area, and falls within a given solid angle. The SI unit for luminance is the candela per square meter (cd/m^2). In comparing radiance to luminance, the radiance measure of a light source (e.g., a light bulb) includes energy at visible and non-visible (UV and IR) wavelengths; however, the luminance of the light bulb includes only energy at the visible (eye-sensitive) wavelengths. The primary instrument for measuring luminance is the photometer, which has a special filter that approximates the eye's sensitivity response. (*Note: The human eye's response to light is discussed in a subsequent section, *Anatomy and Physiology of Color Vision*.*)

Spectroradiometry (also known as spectrometry) is the measurement of light energy at individual wavelengths. The primary instrument used is the spectroradiometer. At the heart of the spectroradiometer is a monochromator, an optical device that transmits a mechanically selectable narrow band of wavelengths of energy chosen from a larger range of wavelengths present at the input. The monochromator has an entrance slit, a dispersive element (e.g., prism, grating, hologram) to spread the energy spectrum, and an exit slit that allows measurement, theoretically, of the amount of energy at each wavelength (Figure 19). However, three factors limit this capability, which defines the resolution of the spectroradiometer. First, the EM spectrum is continuous, not discrete, meaning that an infinite number of wavelengths exist. Second, different dispersive elements (in concert with the geometry of the monochromator) affect how far apart any two wavelengths are spread or separated. The third factor is the physical width of the instrument's exit slit. Consequently, the output of the monochromator is actually a very narrow-band Gaussian intensity distribution of wavelengths. Typically, resolutions of 1-10 nm are available for modern systems, many of which offer selectable resolutions. The tradeoffs of greater resolution (lower resolution values) are reduced sensitivity, precision, and accuracy.

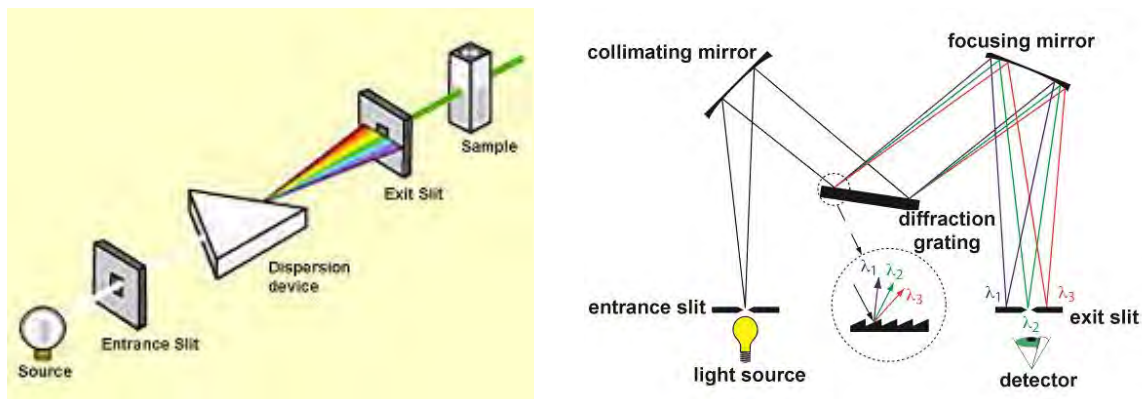


Figure 19. Fundamental design of a monochromator (left); schematic diagram of a monochromator using a diffraction grating as the dispersive element (right) (University of California, Davis).

⁸⁰ The terms *luminance* and *brightness* (as related to light intensity) are commonly, but incorrectly, interpreted as having the same meaning. Brightness is a subjective attribute of light to which humans describe in such relative terms as “dim” and “bright.” Brightness is perceived, not measured. Luminance is the measurable quantity, defined as luminous intensity per unit area projected in a given direction.

The output of the measurement is typically a data table and/or graph of the individual values. Examples of spectroradiometric graphs have been previously presented in Figures 6-8 and 15-16. As for radiance measurements, spectroradiometric measurements can be performed over the entire spectrum or within a specific band of wavelengths. The SI unit for spectral radiance is Watt per square meter per steradian per nanometer ($\text{Watt/m}^2\text{-sr-nm}$).

Color Science

Color has been a subject of interest and investigation for millennia. Philosophers (Aristotle and Democritus), writers and poets (Goethe and Pliny the Elder),⁸¹ physicists (Newton and Young),⁸² physiologists (Helmholtz & Hering),⁸³ psychologists (Fechner),⁸⁴ and mathematicians (Schrödinger and Kempe)⁸⁵ have all contributed to our understanding of color phenomena. Color science is a fundamental field of the sciences dedicated to understanding the creation of colored stimuli, sources of illumination, and ultimately the human perception of color (Fairchild, 2015). It builds upon, and crosses the disciplinary boundaries of chemistry, physics, life sciences, mathematics, and psychology. Color science is used in the design and production of most man-made materials including textiles, paints, plastics, ceramics, and imaging systems, and to specify the properties of diverse natural materials such as skin, plants, animals, and soil.

Color properties.

Up to this point colors have been defined in terms of specific wavelengths of light. This is sufficient for pure (or spectral) colors. However, most colors encountered (perceived) in day-to-day activities consist of combinations of wavelengths. Such colors cannot be defined by wavelength alone. In one scheme (the red-green-blue or RGB scheme) such colors are defined by three color attributes (or properties): *hue*, *saturation*, and *brightness*.⁸⁶ Hue is the property of the color experience that most people assign the commonly used color labels, e.g., red, blue, green, and magenta, but is more definitively defined as the wavelength within the visible spectrum at which the energy is the greatest (i.e., dominant wavelength). Figure 20 presents two sets of three different spectral distributions. Each energy distribution in the set on the left has a different dominant wavelength and will be perceived as different colors or hues. In contrast, each energy distribution in the set on the right has the same dominant wavelength and hence will be perceived as the same color or hue.

Saturation (also known as chroma) is an expression for the relative bandwidth of the visible output from a light energy distribution and refers to the intensity or vividness of a specific

⁸¹ German poet and artist Johann Wolfgang von Goethe (1749-1832) wrote a treatise on the nature, function and psychology of colors in 1810; Roman author, naturalist, and philosopher Pliny the Elder (23-79 CE), wrote extensively about historical knowledge of color in nature and culture in his encyclopedic work *Naturalis historia* (Natural History) published in 77-79 CE, not always distinguishing between fact, myth, and opinion.

⁸² Thomas Young (1773-1829), physicist, was most famous for his experiment demonstrating the wave nature of light.

⁸³ Hermann Ludwig Ferdinand von Helmholtz (1821-1894), physician and physicist, contributed to the physiological basis of color vision, co-developing the trichromatic theory known as the Young-Helmholtz theory; Ewald Hering (1878/1964), physiologist, developed the opponent-process theory of color vision.

⁸⁴ Gustav Fechner (1801-1887), a German physicist and psychologist, studied the perceptual illusion known as the Fechner color effect, whereby colors are seen in a moving pattern of black and white (Bagley, 1902).

⁸⁵ Erwin Schrödinger (1887-1961), mathematician and theoretical physicist, pursued physiological studies of color and developed the wave equation for describing quantum mechanical behavior; Alfred Bray Kempe (1848-1922), mathematician, studied the four-color conjecture that any planar map can be colored with four or fewer colors.

⁸⁶ The use of hue, saturation and brightness values to represent a color is known as an HSB representation; alternately, *brightness* can be replaced with *lightness* or *value*, becoming HSL and HSV representations, respectively.

hue. In the right set of distributions in Figure 20, differing saturations are represented by the steepness of the slopes of the curves. The widest distribution curve represents the lowest saturation; the narrowest distribution represents the highest saturation. As saturation increases, hues (colors) appear more pure; as saturation decreases, colors appear duller or more washed-out. Saturation also can be interpreted as the amount of gray in a color. Saturation can be expressed as a percentage (0-100%), where a 0% saturation makes a hue look medium gray (actually hue becomes meaningless at this value); as saturation approaches 100%, the hue appears more vivid or brighter.

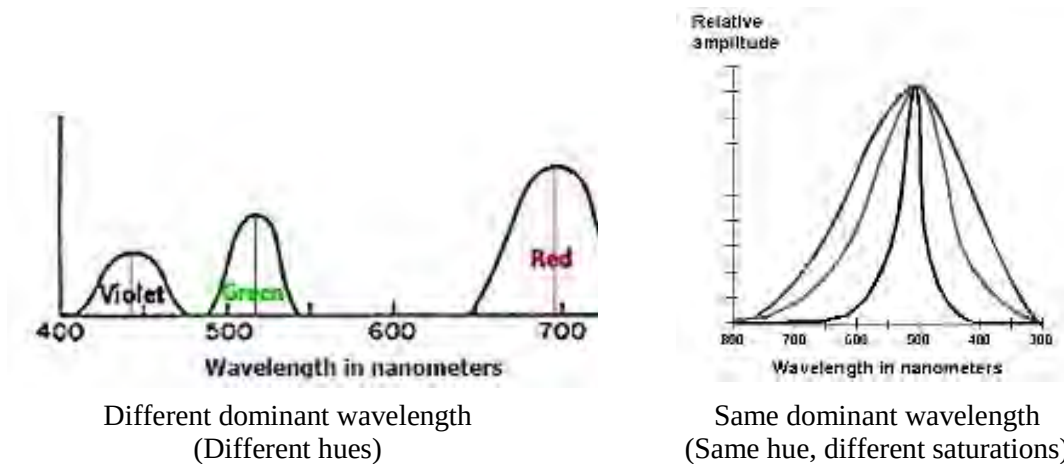


Figure 20. Two sets of visible energy distributions having different dominant wavelengths (left) and the same dominant wavelengths (right).

Brightness (also known as lightness or value) is an expression of the intensity of the energy output of a visible light source. It also can be thought of as how light or dark a given hue is. It represents the relative degree of black or white mixed with a given hue. Adding white makes the hue lighter (creates tints) and adding black makes it darker (creates shades). Similar to saturation, brightness can be expressed as a percentage (0-100%), where black is 0%, and white is 100%. At 0% brightness, both hue and saturation are meaningless.

The relationship between these three properties of color is demonstrated in Figure 21. Across the top (Row 1), the hues (colors) in the visible spectrum are presented. An arbitrary hue (a blue) has been selected (Row 2). This sample hue is a spectral hue and is by definition fully saturated.⁸⁷ So, only less saturated versions are possible, which are presented in Row 3, to the left (less saturation) side of the fully saturated version. An arbitrary saturation is selected from this row and is expanded to present some of the possible brightness values in Row 4.

⁸⁷ A spectral hue consisting of only one wavelength is fully saturated; however all fully saturated hues do not have to be spectral hues.

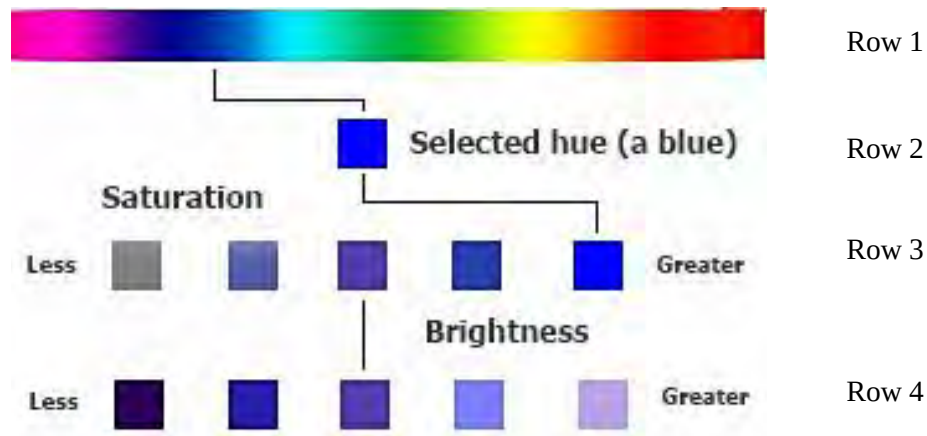


Figure 21. The relationship between the three properties of color: hue, saturation, and brightness.

Before closing the discussion of the three color properties, it is instructive to revisit the concepts of tint and shade in association with brightness, and add a third concept of tone, which is associated with saturation. These three terms are used to describe how a color can vary from its original hue. These new concepts can be viewed from two perspectives, producing two scales. The first perspective pertains to the subtractive mixing of pigments; the second deals with additive mixing of light (Cotnoir, 2016). The first scale indicates the amount of black, white, or gray (toning) pigment added to a hue (Figures 22 and 23 [top]). In this model, the scale shows the effects of adding white to a given hue to produce various tints, adding black to produce varying shades, and adding black *and* white (i.e., gray) to produce different tones. When a pigment hue is “tinted” by adding white, a lighter version of the hue results; when a pigment hue is “shaded” by adding black, a darker version results; and, when a pigment hue is “toned” by adding gray (white and black), hue saturation is reduced, tending in the extreme to a gray result. In Figure 22, an arbitrary hue (red) has been selected to which varying amounts of white (left) and black (right) is added to produce a ranges of tints and shades of the red hue, respectively. White (at the extreme left) and black (at the extreme right) are not considered either tints or shades, respectively. An expanded representation of tints, shades, and tones is presented in Figure 23 (top).

Figure 23 (bottom) presents a scale for hue saturation for the additive mixing of light model. In this color model, saturation depends on how much or how little other hues are represented in the color. This is in accordance with a previous discussion stating that saturation refers to the dominance of hue in the color. “Pure” hues are presented at the outer left edges. On the right edges, all hues present at full intensity result in white; all hues at medium intensity result in gray; and black is the total absence of light.

The relationship between tints, shades, and tones is presented in a color wheel and a pictorial diagram in Figure 24.

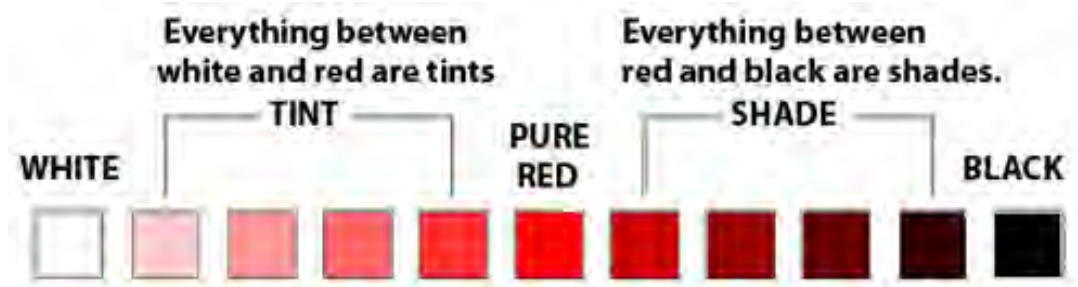


Figure 22. Tints and shades of a red hue, obtained by adding white or black, respectively.

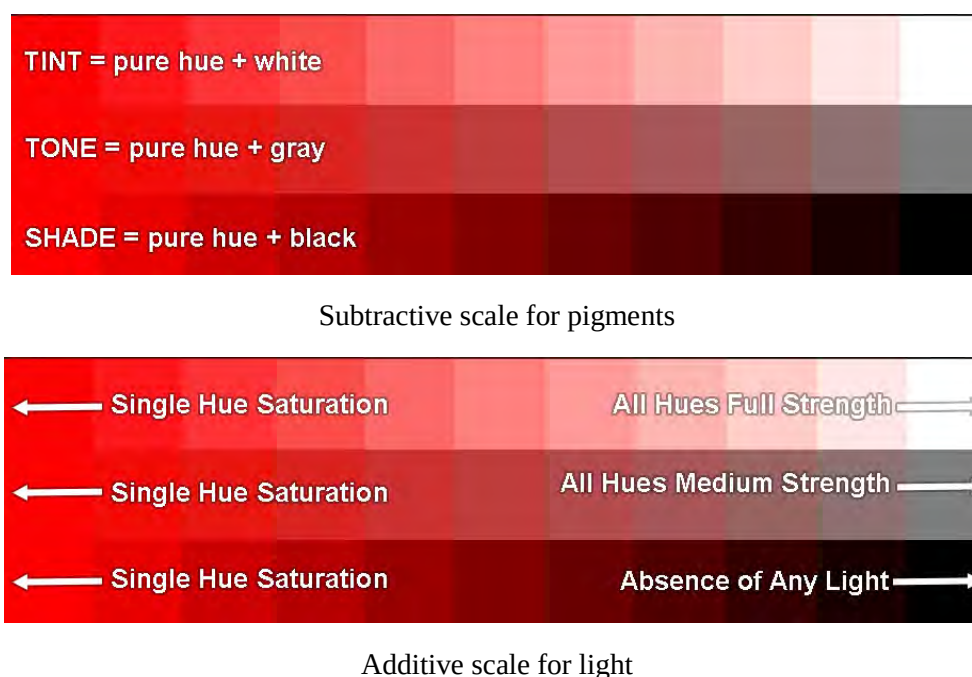


Figure 23. Scales for tints, shades, and tones for subtractive pigment mixing (top) and for saturation in additive light mixing (bottom) (adapted from Cotnoir, 2016).

Color wheels.

A color wheel (or color circle) is a pictorial representation of colors arranged to present their chromatic relationship. Newton is credited with the first depiction of a color wheel in the mid-1660s (Figure 5, p. 15). Since then a number of variations have been presented, and many formats are in use today. However, the fundamentals of the chromatic relationships are the same. Illustrative examples of color wheels are presented in Figure 25.⁸⁸

⁸⁸ Readers again are cautioned that colors presented in this paper are provided for general color information and illustration purposes only. Because of the differences in computer monitors, printers, and other hardware and software combinations, depicted colors are intended to be used as approximations, rather than definitive representations.

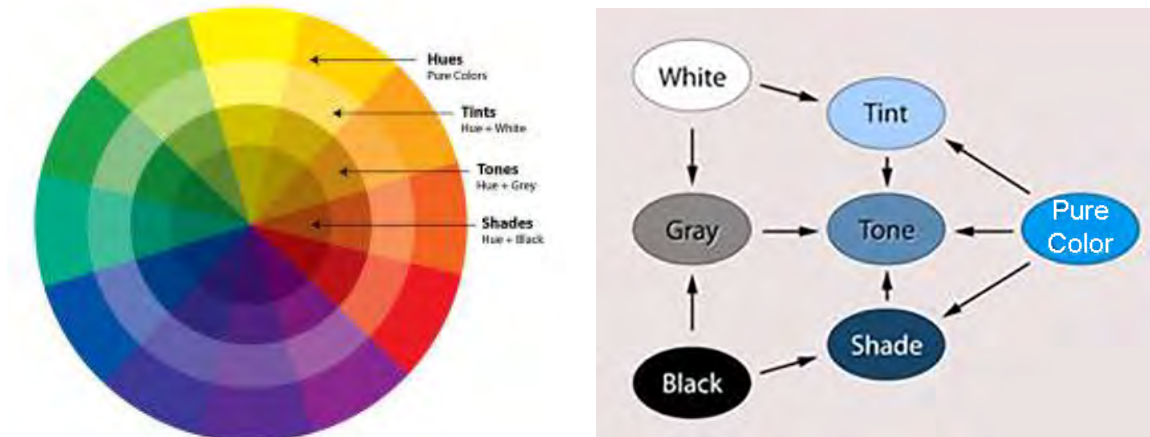


Figure 24. The relationship between tints, shades, and tones in a color wheel (left) and diagram (right).



Figure 25. Examples of color wheels.

A color wheel is formed by positioning three *primary* colors (hues) equidistant from one another and creating connections between the primaries using *secondary* and *tertiary* colors. In traditional color theory (used in paint and pigments), the primary colors are the three pigment colors that cannot be mixed or formed by any combination of other colors. All other colors are derived from these three primary hues. In Figure 26 (top, left), the primary colors of red, blue, and yellow are depicted. The secondary colors are formed by mixing pairs of the primary colors: orange (red with yellow), violet (red with blue),⁸⁹ and green (violet with yellow) (Figure 26 [top, middle]). Tertiary colors are formed by mixing a primary color with a secondary color; these hues have two-word names: red-orange, red-violet, blue-violet, blue-green, yellow-green, and yellow-orange (Figure 26 [top, right]).

Two additional chromatic associations create *complementary* and *analogous* colors. Colors that are opposite each other on the color wheel are considered to be complementary colors (e.g., red complements green; blue complements orange) (Figure 26, bottom, left).

⁸⁹ Violet is used in this discussion; in some color wheels, violet is replaced with purple. The spectral color violet is not a purple according to traditional color theory, but purple is in common English usage as the color between red and blue.

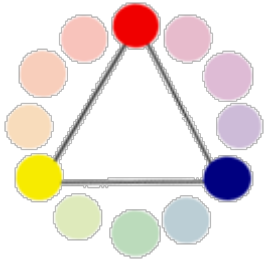
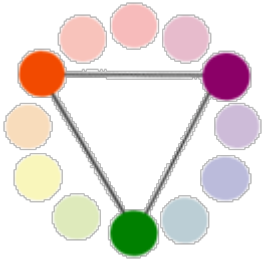
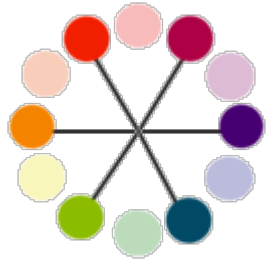
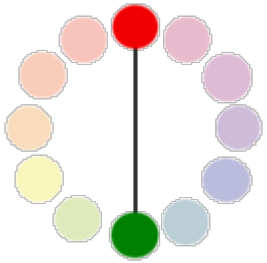
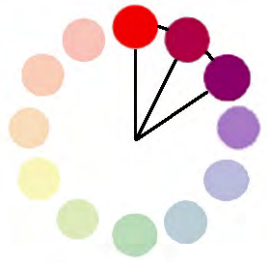
		
Primary colors (Red, blue, yellow)	Secondary colors (Orange, violet, green)	Tertiary colors (Red-orange, red-violet, blue-violet, blue-green, yellow-green, yellow-orange)
		
Complementary colors (e.g., red-green)	Analogous colors (e.g., red, red-violet, and violet)	

Figure 26. Color terminology.

Analogous colors are groupings of three colors located close together (side-by-side) on a color wheel, sharing a similar hue and saturation, with one being the dominant color, which tends to be a primary or secondary color, and two on either side, which tend to be tertiary colors. In the example, the analogous colors depicted are red, red-violet, and violet (clockwise in Figure 26 [bottom, right]). Analogous color schemes are often found in nature. Figure 27 presents an alternative 12-step color wheel frequently used in art schools, using yellow, red, and blue as primaries and violet, orange, and green as secondary colors.

Additive and subtractive color systems.

As illustrated in the discussion of color wheels above, color theory is based on the use of three colors, when mixed together, can produce other colors. These former colors are known as *primary* colors and can vary according to application. Colors can be mixed via two methods (or systems): additive and subtractive. *Additive* color mixing is the system usually demonstrated in a physics classroom via the overlapping of light sources and is the method by which colors are produced on color displays, e.g., televisions, phones, tablets, and computer monitors. Digital color cameras also use additive color mixing. *Subtractive* color mixing is the color system employed in printing and painting. It is also the type of color mixing employed when filters are used in front of white light sources (see *Color filters* section). Pictorially, additive and subtractive color mixing systems are depicted in Figure 28.

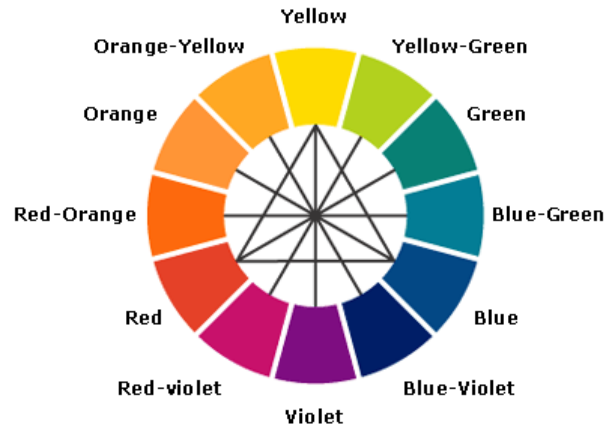


Figure 27. An alternative color wheel showing chromatic associations (e.g., complementary and analogous colors) (Cornell University, 2006).

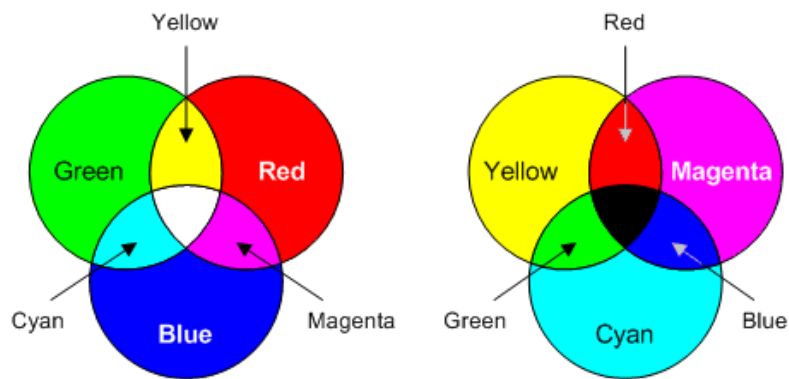


Figure 28. The additive (left) and subtractive (right) systems of color mixing.

In additive color mixing, the three commonly used primary colors are red, green, and blue (RGB). Combinations of these primary colors can produce colors in the visible spectrum. Equal amounts of all three result in white light. Because these colors are added together to make white, they are known as additive primaries. Mixing equal amounts of two primary colors together produces what are known as the secondary colors. These are: yellow (red + green), cyan (green + blue), and magenta (blue + red). Examples of unequal additive mixing include: orange (one part green + two parts red) and brown (one part green + four parts red). For the additive secondary color of cyan, it is defined by light with a dominate wavelength between 490-520 nm and is associated with the color names of aqua, teal, turquoise, aquamarine and others described as blue-green in color (Figure 29). The additive RGB color system is one (and the most common) of the color standards used in industry.

In subtractive mixing, the three primary colors are cyan, magenta, and yellow. When all three are overlapped equally, all the light is subtracted, producing black, the absence of light. Mixing equal amounts of two subtractive primary colors produces the secondary colors of red (magenta + yellow), green (cyan + yellow), and blue (magenta + cyan).

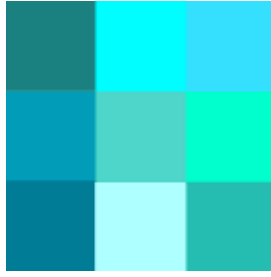


Figure 29. Color range of cyan in the additive color mixing system.

While some subtractive color images are projected (e.g., color slides), the two major subtractive color mixing industries, printing and photography, are the result of reflection and absorption (Stone, 2003) (see *Color printing* and *Color photography and cinematography* sections).

While the physical mixing of paints is often described as purely subtractive mixing, in reality a component of additive-averaging mixing is present. Most light bounces around and interacts with grains of all colorants in the mixture before emerging, so each colorant will influence the color of the light. However, unless the paints involved are perfectly transparent, some light always will be back-scattered off particles of one or more colorant. The first process is subtractive; the second by itself results in additive-averaging mixing. Thus, even if two completely opaque paints do not reflect any common wavelengths, their mixture still will reflect some light because of the contribution of the additive-averaging component (Briggs, 2007a).

In general, additive color mixing is associated with light emission, and subtractive color mixing is associated with light absorption and reflective processes. Note the primary and secondary colors are reversed in the two mixing methods. The primary colors are red, green and blue in additive mixing but are the secondary colors in subtractive mixing; cyan, magenta, and yellow are the primary colors in subtractive mixing but are the secondary colors in additive mixing.

Color spaces and models.

The term *color space* refers to an organized set or range of colors (also referred to as a *color gamut*). This term is frequently confused with the concept of a *color model*, which is a mathematical construct that describes a range of colors (the color space) as a set of coordinates (typically 3 or 4), i.e., hue, saturation, chroma, lightness, or brightness, (Cohen, 2001). It is useful to visualize a color model as being a mapping of a set of numerical values (coordinates) to a set of colors, and the color space as being a set of constraints upon those numbers (Rodney, 2005). However, many discussions of color (including this one) tend to use the terms *color space* and *color model* interchangeably.

Each point in a color space represents a specific color. Color spaces are important for (but not limited to) color quality-control in the manufacturing and graphics industries (Kuehni, 2013). Color spaces also are useful in understanding the color capabilities of a particular color capture or rendering device (e.g., cameras, scanners, displays, and printers). Any discussion of color

spaces will be better appreciated if their purpose is defined in terms of application. The most practical applications involve capturing objects and scenes and then reproducing them as images (i.e., copies of the original scenes). In addition, these images will, in the many steps in this process, be stored in memory (as image files) in different color spaces. So, understanding the different color spaces will aid the understanding of how colors present in the original scenes are transformed into different colors in the scene's final presentation (see *Color management* section).

Specific color spaces can be presented as 3D volumes (Figure 30), but graphical comparisons of color spaces frequently are presented using two-dimensional (2D) slices from their 3D volumes (Figure 31). Device-specific color spaces typically are presented relative to some reference space. The most used reference color space is the device-independent space defined by the Commission International de l' éclairage (International Commission on Illumination) (CIE) in 1931. This space attempts to describe all colors visible to the human eye based upon the average response from a sample of individuals with "normal" color vision (termed as a "standard colorimetric observer").⁹⁰ A number of color spaces (CIE- and non CIE-based) are introduced and briefly described in this section.

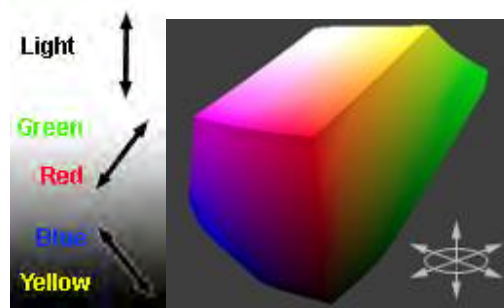


Figure 30. A representative 3D volume color space (adapted from Cambridge in Colour, 2016a).

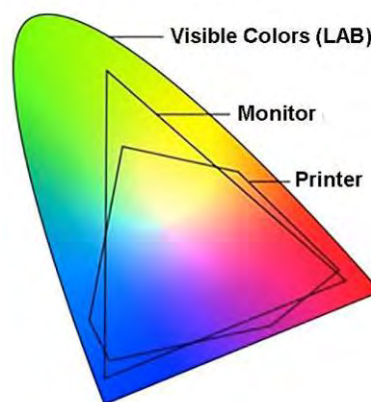


Figure 31. Example of a 2D comparison of three color spaces: visible colors based on a representative CIE color space, computer monitor, and printer.

⁹⁰ The CIE has two specifications for a standard observer: the original 1931 specification and a revised 1964 specification. In both cases the standard observer was a composite of small groups of individuals (about 15-20) and is considered representative of normal human color vision. For color-matching studies, the observers made viewings through a 2-degree (2°) hole, giving rise to the term 2° standard observer.

The CIE 1931 system characterizes the entire gamut of human-perceivable colors using a luminance parameter and two color coordinates x and y ,⁹¹ which specify a specific color point on a CIE chromaticity diagram (Figure 32, left). Using the fact the human eye has three different types of color sensitive cones (see *Anatomy and Physiology of Color Vision* section), the response of the eye can be described in terms of three "tristimulus values." Any color on the CIE chromaticity⁹² diagram can be considered as a mixture of the three CIE-defined primaries. This mixture may be specified by three numbers X , Y , Z , called tristimulus values. The calculation of the chromaticity coordinates for a given colored object involves the multiplication of its spectral power at each wavelength by the weighting factor from each of the three CIE color-matching functions. Summing these contributions gives the three tristimulus values, from which the chromaticity coordinates are derived (Williamson & Cummins, 1983). The color of any light-emitting device (e.g., lightbulb, flame, gas or electrical discharge, LED, or phosphor) can be completely and explicitly defined by a CIE x,y coordinate. The color of any non-emissive (reflective) material (e.g., paint, paper, fabrics, skin, fur, leaf, petal, etc.), or any transmissive filter (e.g. stained glass) also can be defined by a CIE x,y coordinate, but only for a specified source of illumination.

The CIE primaries are not real colors, but convenient mathematical constructs. Nevertheless, the tristimulus values uniquely represent a perceivable hue, and different combinations of light wavelengths giving the same set of tristimulus values will be indistinguishable in chromaticity to the human eye.

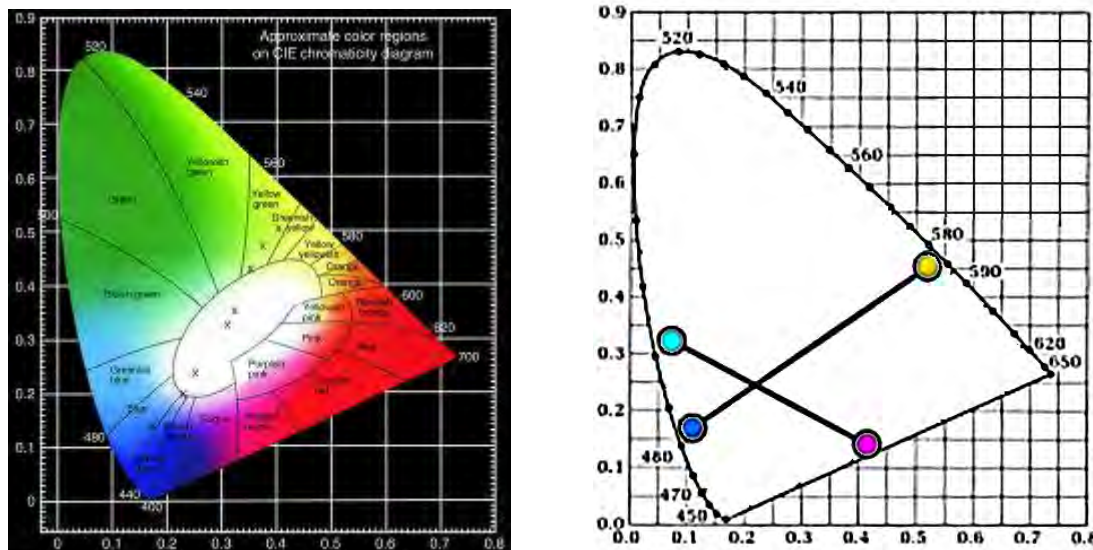


Figure 32. The CIE 1931 color model diagram (left), featuring color regions and pure spectral colors (wavelengths in nm); possible colors resulting from mixing two colors on the diagram fall along the corresponding connecting line (right).

⁹¹ The chromaticity coordinates x,y (and z) always add up to 1 (i.e., $x+y+z = 1$); therefore, only x and y are required to specify any color, and the diagram can be 2D.

⁹² Chromaticity is a 2D description of color, which corresponds to the combination of hue and saturation (purity), omitting the third dimension of luminance.

The numbers that run along the boundary of the chromaticity diagram correspond to the pure wavelengths of the visible spectrum (typically 400-700 nm) (Figure 32, left).⁹³ The bottom boundary connecting the 400- and 700-nm points have no numbers, as they do not represent real spectral colors. A straight line between any two points (colors) on the diagram represents all of the colors that can be produced by mixing the two mixing colors; different points on a line represent different amounts of mixing of the two end-point colors (Figure 32, right). In this figure, two mixing pairs are presented (indicated by two lines). These lines intersect at a point having the same chromaticity but being produced by two different mixing combinations. The two mixing combinations will appear as the same color to an observer; this effect is called metamerism (see *Metamerism* section).

If any three points (colors) are selected, the area within the triangle represent the range of colors capable of being produced by mixing varying amounts of the three colors (i.e., color gamut). (See Figure 31, p. 44, for examples of a representative printer and monitor). Note: The chromaticity diagram is commonly used to evaluate a specific color against a color gamut. The presumption is that if the chromaticity of the color lies within the gamut boundary (typically a triangle defined by three primaries), then the color may be reproduced on that device, or may be represented by that color system. But, color has three dimensions and a chromaticity diagram presents only two dimensions; the missing dimension on the diagram is luminance. Because of this incompleteness, using a chromaticity diagram to determine whether or not a color is within a specific gamut may be misleading.

A sizable number of color models have been developed, each having varying suitability for specific applications. The most commonly encountered models include RGB (Red, Green, Blue), CMY/CMYK (Cyan, Magenta, Yellow, black),⁹⁴ HSL/HSB/HSV (Hue, Saturation, Lightness [Brightness/Value]), and Munsell, as well as a number of variants on the CIE 1931 model (Ford & Roberts, 1998; Adobe Systems, 2016). Some of the more common models are summarized as follows:

- RGB – Perhaps, the most common color model; based on the tri-chromatic theory of color; non-linear with visual perception; used in CRTs and many computer displays; its associated color space may be visualized as a cube with the three axes corresponding to red, green, and blue (Figure 33). In this model, the hidden rear corner is black (red = green = blue = 0), while the opposite front top corner is white (red = green = blue = 255) (for an 8-bit per channel display system) (see also *White and black points* section). The RGB model is an additive system where colors are created by mixing spectral light in varying combinations. Note the maximum values of 255 (full saturation) are based on an 8-bit color system; the cubic solid could just as easily be normalized and expressed as having maximum values of 1 for each fully saturated color.

⁹³ This boundary edge is also known as the *spectral (or spectrum) locus*.

⁹⁴ The use of “K” for black in the CMYK acronym has two undocumented explanations. The first asserts the “K” was used to avoid confusion with the “B” already was associated with the color blue; the second states that the “K” is associated with the “key plate” used to align the other color plates, but with no explanation as to choice of the word *key* (Gatter, 2005).

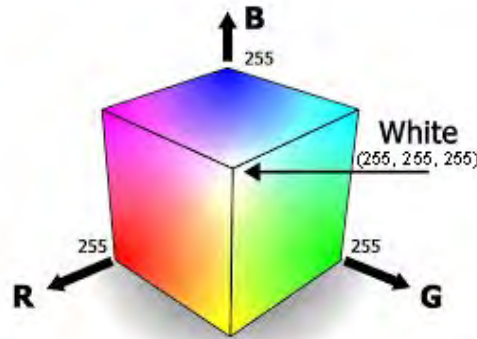


Figure 33. RGB color model for an 8-bit per color channel display.

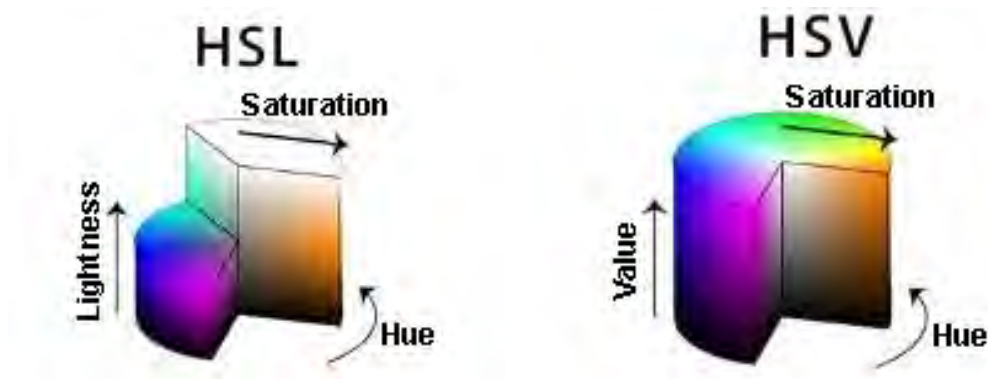
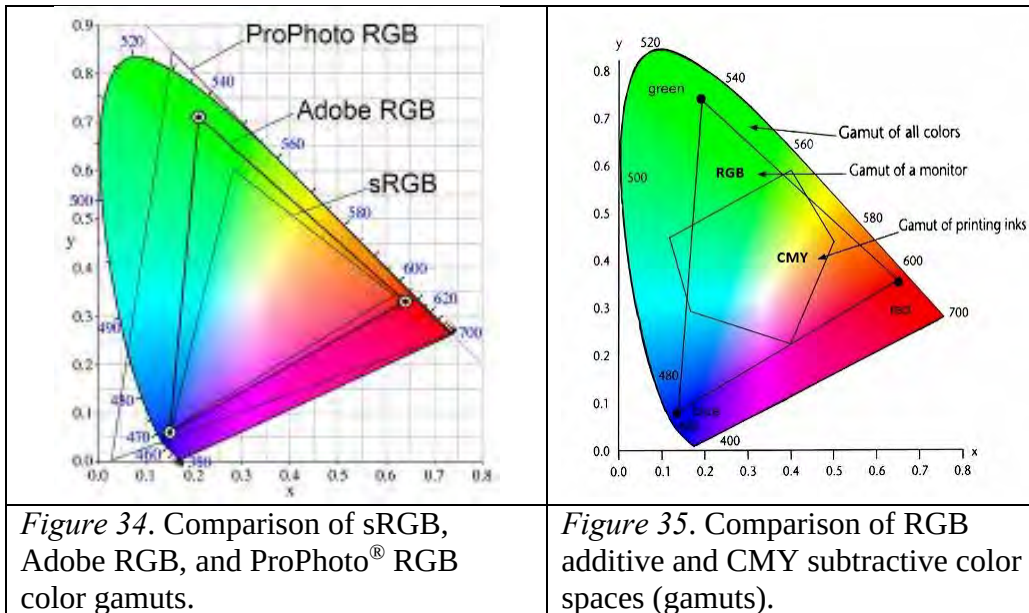
While newer display technologies constantly are emerging, currently the most used color model (space) for televisions, phones, tablets, digital camera, printers, and computer displays is sRGB (standard RGB),⁹⁵ which has its RGB primaries defined by the chromaticity coordinates: R (0.64, 0.33), G (0.30, 0.60), and B (0.15, 0.06). It has been the color space of choice for most website designers because sRGB image files are handled easily by virtually all most existing software and hardware. In spite of its wide use, the sRGB color gamut encompasses only 35% of the visible colors specified by CIE. Fortunately, there are two “larger” RGB-based color spaces rapidly growing in use by high-end graphics designers and photographers. These are Adobe RGB⁹⁶ and ProPhoto® RGB.⁹⁷ The only major obstacle is that only a small (but increasing) segment of display devices (e.g., televisions, printers, and computer monitors) can effectively utilize these enhanced color spaces. Consequently, even when an image file is created in one of these enhanced color spaces, typically it will be converted to the sRGB color space for display, often with dull, muted tones (e.g., a loss of original vibrancy) but occasionally with noticeably incorrect colors. A comparison of these three color gamuts is presented in Figure 34.

- CMY/CMYK – A counterpart of the RGB model but based on subtractive color. Subtractive colors are produced when pigments in an object absorb certain wavelengths of white light while reflecting the rest. The primary colors of CMY are the secondary colors of RGB. The CMYK color space (gamut) is much smaller than the RGB color space (Figure 35). It is the color space employed in printers via inks.
- HSB/HSV/HSL – A cylindrical coordinate model based on logical aspects of color. Values are transformations of RGB values; used in image editing software. HSB is essentially the same as HSV, but HSL differs slightly. In all of these models, hue (H) defines the color itself, e.g., red, blue, yellow; and saturation (S) indicates the degree to which the hue differs from a neutral gray. Hue and saturation are the color-carrying components of the models; Value (V) and lightness (L) indicate the level of brightness. HSL and HSV color spaces are shown in Figure 36.

⁹⁵ sRGB was co-developed by Microsoft® and Hewlett-Packard in the 1990s.

⁹⁶ The Adobe RGB color space is a RGB color space developed by Adobe Systems, Inc., in 1998.

⁹⁷ ProPhoto RGB (also known as Reference Output Medium Metric RGB) was developed by Kodak Research Laboratories in the late 1990s-early 2000s.



- Munsell – Based on a 3D model in which each color is comprised of three attributes of human color vision: hue (dominant wavelength), value (brightness/lightness/darkness), and chroma (color saturation) (Figure 37). Developed in 1898 by American artist Albert Munsell (1905), the system divides hue into 100 equal divisions around a color circle. He modeled his system as a globe, around whose equator runs a band of colors. The vertical axis is a scale of neutral gray values with white at the North Pole and black at the South Pole. Extending outward from the axis at each gray value is a progression of color from neutral gray to full saturation. The *Munsell Book of Colors* (Munsell Color, 2015) is a contemporary well-known source of color matching information used by printers and designers.

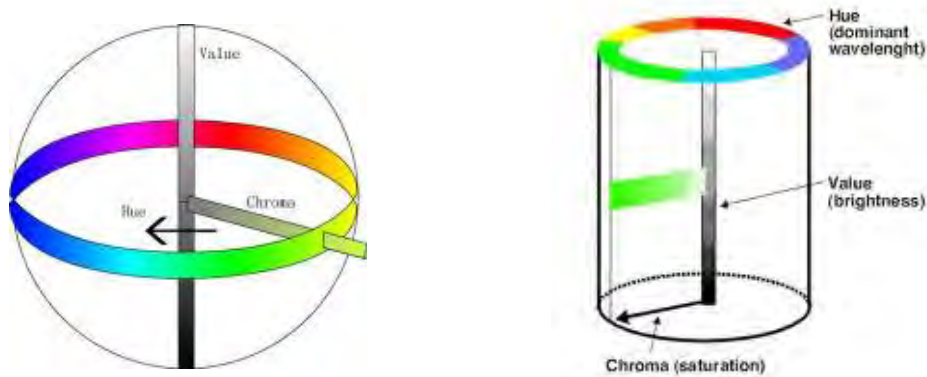


Figure 37. Two presentations of the Munsell color model, illustrating hue, value, and chroma (Kalloniatis & Luu, 2007).

- CIE variants – The CIE visible color space is expressed in several forms, which include the following: CIE x,y,z (1931), CIE L^*u',v' (1976), and CIE $L^*a^*b^*$. Each contains the same colors but distributes them differently (Cambridge in Colour, 2016a) (Figure 38).
 - CIE x,y,z is based on a direct graph of the signals from each of the three types of color cones in the human eye. These also are referred to as the X, Y and Z tristimulus functions.
 - CIE L^*u',v' was created to correct for the CIE x,y,z distortion by distributing colors roughly proportional to their perceived color difference. A region twice as large in u',v' will therefore also appear to have twice the color diversity.
 - CIE $L^*a^*b^*$ remaps the visible colors so they extend equally on two axes (usefully filling a square shape). Each axis in the $L^*a^*b^*$ color space also represents an easily recognizable property of color. It is often referred to as CIELAB. CIELAB is a device independent color space, which is important in the management of color (see *Gamma correction* and *Color management* sections).

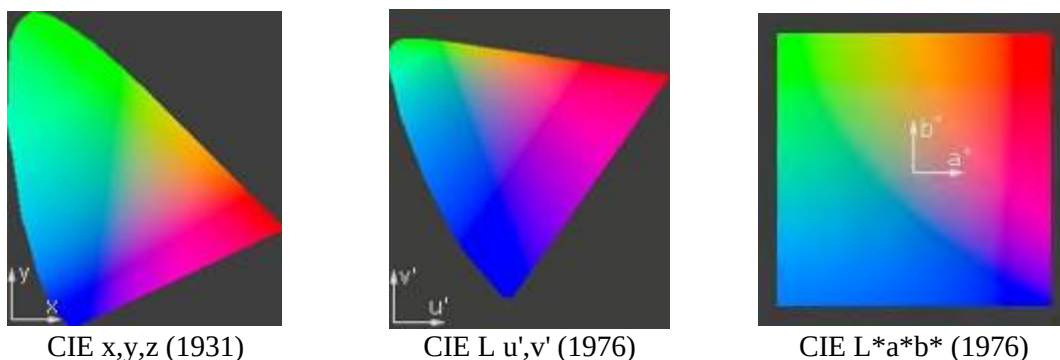


Figure 38. Comparison of CIE color model variants: CIE x,y,z (1931), CIE L^*u',v' (1976), and CIE $L^*a^*b^*$ (1976) (Cambridge in Colour, 2016a).

- $Y'CbCr$ ⁹⁸ – One of two primary color spaces (with RGB) used to represent “digital” component video (e.g., high definition [HD] television). The difference between $Y'CbCr$ and RGB is $Y'CbCr$ represents color as *luma* (luminance) (Y') and two *color difference* signals (Cb and Cr), while RGB represents color as three hues: red, green and blue. The Cb and Cr components indicate the intensities of the blue and red components relative to the green component (Figure 39), i.e., Cb and Cr are the blue-difference and red-difference chroma components, respectively. This color space exploits the properties of the human eye, which is more sensitive to light intensity changes and less sensitive to chrominance (hue) changes. As is described in the *Color management* section, when the amount of information in an image (file) needs to be minimized (compressed), this model allows the brightness (Y') component to be stored with higher accuracy while allowing greater reduction of the Cb and Cr components.

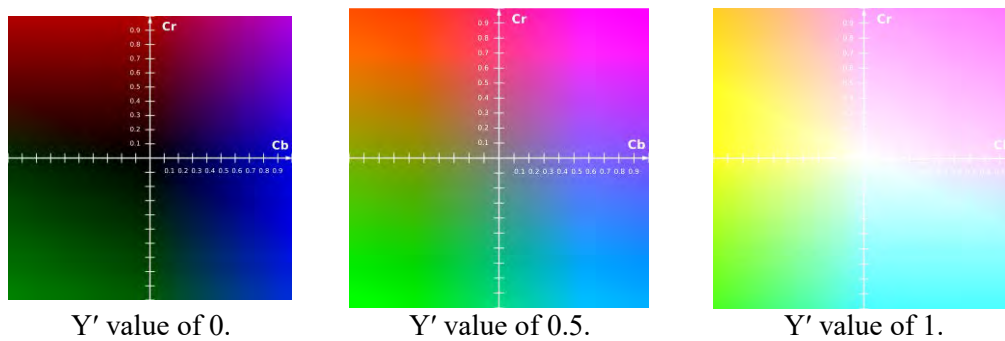


Figure 39. CbCr plane of the $Y'CbCr$ color space, with Y' values (right to left) of 0, 0.5, and 1 (Source: Simon A. Eugster).

Pointer's gamut.

A somewhat distinctive color space, one driven by the real world, is known as *Pointer's gamut*, developed by M. Pointer in 1980. Its purpose was to provide a representation of the gamut of real (actual) surface (reflective) colors of objects encountered (seen) by the human eye. It is important to appreciate that every color that can be reflected by the surface of an object of any material would fall inside Pointer's gamut. This is important because a vast number of industries are inherently concerned with the accurate reproduction of real-world colors (both as suppliers and consumers) (Li, 2013). Note Pointer's gamut is the set of colors that can be reproduced using *subtractive* color mixing, which is a subset of the set of colors reproducible using *additive* color mixing.

Pointer's gamut is plotted on the CIE 1931 x,y (left) and CIE 1976 CIE u',v' (right) chromaticity diagrams in Figure 40. Pointer's gamut covers approximately 48% of the colors in the CIE 1931 x,y color space (Jansen, 2014). Its irregular shape explains why it's difficult to manufacture a display capable of reproducing all colors in the Pointer's gamut using the three RGB primaries. In fact, as shown later in this paper, it's impossible to create an RGB color space

⁹⁸ $Y'CbCr$ also is called $YPbPr$ when used for analog component video, although $Y'CbCr$ is commonly used for both systems, with or without the prime symbol.

using real primaries (as opposed to imaginary primaries) that covers a true 100% of the Pointer's gamut. To accomplish this feat a color model with at least 4 primaries is required.

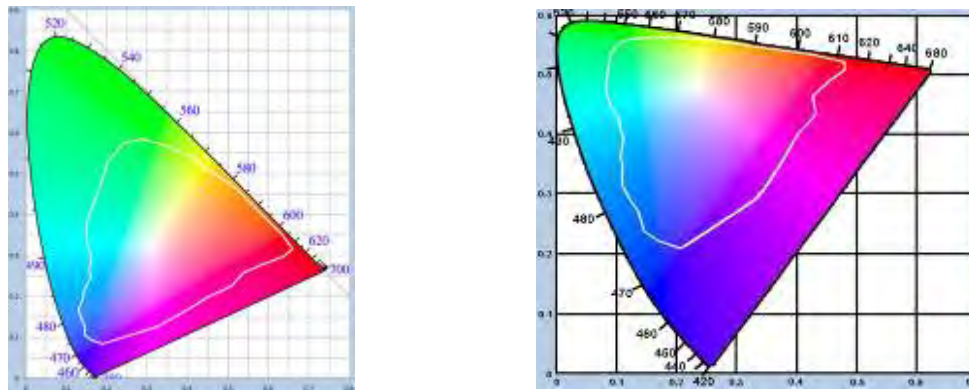


Figure 40. Pointer's gamut as plotted on the CIE 1931 x,y (left) and CIE 1976 CIE u',v' (right) chromaticity diagrams.

Pointer's gamut covers 46% of the colors in the CIE 1976 u',v' color space (Jansen, 2014). When comparing the Pointer's gamut in the CIE 1931 x,y chromaticity diagram to the Pointer's gamut in the CIE 1976 u',v' chromaticity diagram, a large difference in the colors outside of Pointer's gamut can be noted. In the CIE 1931 x,y chromaticity diagram these are mostly green and cyan hues, while in the CIE 1976 u',v' chromaticity diagram they are mostly blue and violet hues. This is due to the fact the linear density along the spectral locus in the CIE 1931 x,y chromaticity diagram differs significantly from that in the CIE 1976 u',v' chromaticity diagram. In the CIE 1931 x,y chromaticity diagram, peak sensitivity is at 497 nm (cyan); in the CIE 1976 u',v' chromaticity diagram, the peak is at 483 nm (azure).⁹⁹

Pointer's gamut was based on measurements of approximately 4000+ samples, and therefore is only an approximate definition of a real-world surface reflective color gamut. Since its introduction, a number of additional efforts have expanded the sample size, with indications that Pointer's original gamut is smaller than indicated by more recent investigations (Li, Luo, Pointer, & Green, 2013).

The CIE 1931 chromaticity diagram – additional features.

In the CIE color space system, the spectral power distribution (SPD) of light is converted into a luminance parameter and two chromaticity coordinates (x,y). These coordinates map colors with respect to hue and saturation on the 2D CIE chromaticity diagram. As presented in the description of color spaces above, several revisions (e.g., 1960, 1976) have been made to the original CIE 1931 chromaticity diagram, but it remains the most widely used version.

Because of the dominant role that chromaticity diagrams play in commercial color presentations, it is worthwhile to provide a more in-depth look at how these 2D depictions of 3D

⁹⁹ As discussed earlier, color names are somewhat variable. The color azure is a light shade of blue, sometimes compared to the color of the sky on a clear day.

color spaces provide validity, focusing primarily on the original CIE 1931 version. The key elements in this transformation are (Blackwell, 2012):

- The chromaticity diagram is a 2D simplification of the 3D color cube defined by the series of tristimulus vectors (RGB) each having a range of values from 0 to 1 (Figure 41a). The vector end points having coordinates (0,0,0) and (1,1,1) represent the colors black and white, respectively (Figure 41b). Any other vector point (r,g,b) within the cube represents any of the other possible colors that can be created by mixing combinations of red, green, and blue (Figure 41c).
- A plane can be constructed using the maximum points of the three color axes. It forms an equilateral triangle (Figure 41d). Anywhere on this plane, the sum of the three coordinate values equals 1 (giving the plane the name of the *unit plane*). On a plane, it only takes 2 points to locate any point. The missing third dimension is the luminance value.
- Using the CIE tristimulus system, the mapping of the tristimulus values of the colors in the visible spectrum unto the unit plane is called the spectral locus (Figure 41e), which forms the outline boundary of the plotted on chromaticity diagram Figure 41f). The spectral locus contains the full gamut of colors humans are capable of seeing.
- Figure 41g presents the classical presentation of the CIE 1931 chromaticity diagram with wavelength-labeled spectral locus and x,y axes.
- A visually observable feature of the diagram presentation in Figure 41g is a centralized point that appears white. The point, labeled “E” in Figure 41h, is known as the *equal energy point* and has the chromaticity coordinates (x,y) = ($\frac{1}{3}, \frac{1}{3}$) (Boyce, 2014). It is also known as a white point, therefore often designated as “W” (see *White and black points* section). It is worth iterating the saturation of a color increases as its chromaticity coordinates move away from the equal energy point towards a point on the spectral locus.

The representations of the CIE 1931 chromaticity diagram presented in Figures 32 (left, p. 45) and 41g present useful color regions, even if somewhat arbitrarily named (e.g., Bluish green, Yellow, Orange, and Purple). As discussed, the pure spectral colors (hues) are distributed around the edge (outer boundary outline) of the diagram. These consist of a selected number of visible spectral wavelengths typically over a range of 400 to 700 nm and are marked by tick-marks. However, many variants of the diagram are encountered in both the scientific and commercial literature (e.g., presenting light source, display, and printer color gamuts). Depending on the purpose of presenting the diagram, most will have added features beyond the simple presentation of the color regions. These features include the Planckian locus, standard illuminants,¹⁰⁰ and white point.

Planckian (Blackbody) locus.

Close to the chromaticity diagram equal energy point (E) labeled in Figure 41h a specialized curved line in the x,y space known as the Planckian¹⁰¹ or blackbody locus (Figure 42, top). It is defined as the path (or locus of points) the color of a blackbody radiator would take as its blackbody (color) temperature (in °K) changes (see also Figure 18, p. 34). The

¹⁰⁰ A *standard illuminant* is a theoretical source of visible light with a defined spectral power distribution (see *Standard illuminants* section).

¹⁰¹ Named in honor of Max Planck, the German physicist who developed Planck’s Law, a formula for determining the spectral power distribution of a light source based on its temperature.

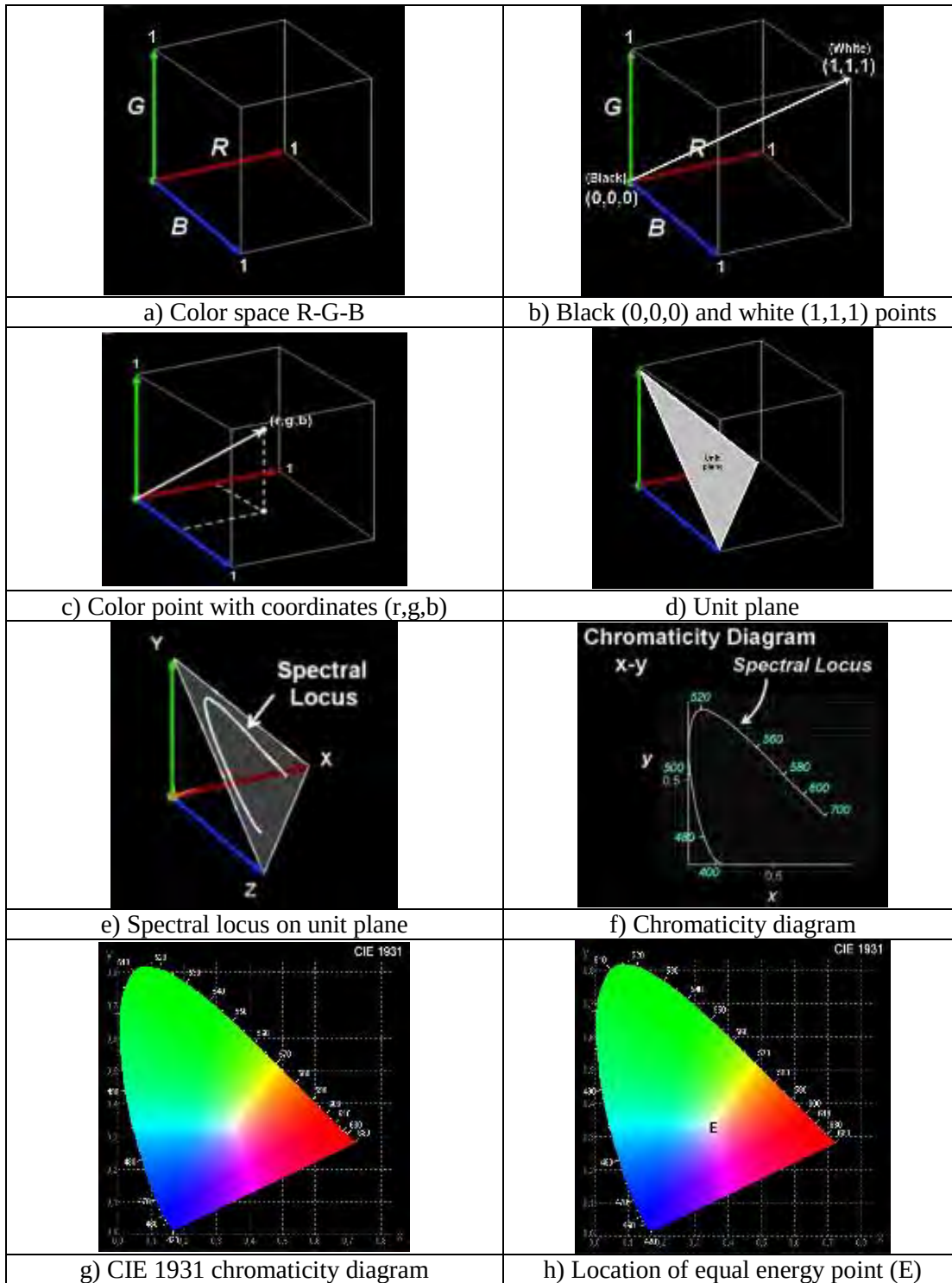
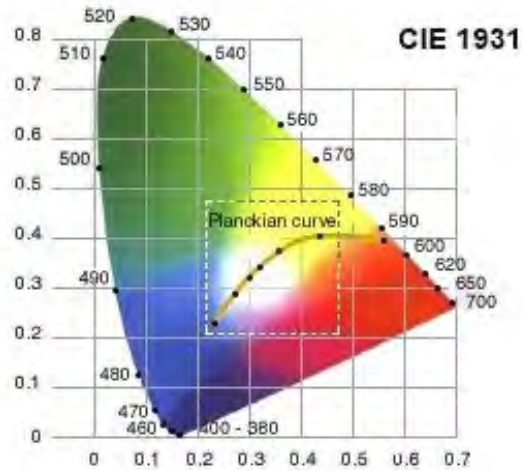
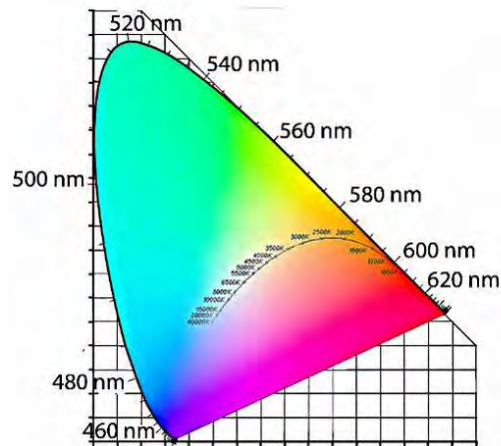


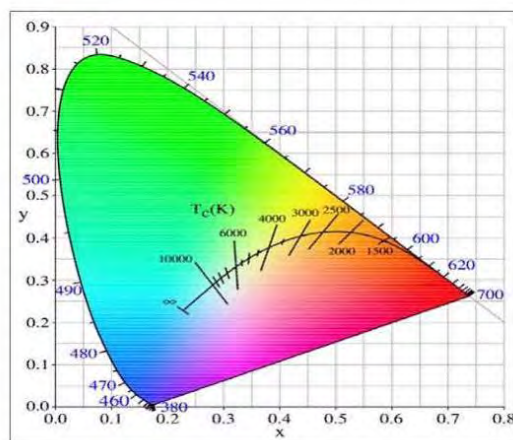
Figure 41. The transformation of 3D color space into a 2D chromaticity diagram (adapted from Blackwell, 2012).



Planckian locus



Planckian locus with °K color temperatures



Planckian locus with constant CCT temperature bars

Figure 42. Additional features on the CIE 1931 chromaticity diagram.

determination of the locus of chromaticity coordinates defined by blackbody radiators is considered a colorimetric landmark in the development of the CIE 1931 chromaticity diagram. Points on the locus can be calculated by colorimetrically integrating the Planck function at many different temperatures, with each temperature specifying a unique pair of 1931 x,y chromaticity coordinates on the locus (Herandez-Andres, Lee, & Romero, 1999).

The methodology behind the production of the blackbody locus is summarized by MacEvoy (2015):

If emittances of blackbodies are converted to lumens and then their energy differences standardized to obtain light profiles of equal luminance, the resulting relative spectral emittance profiles (or illuminants) can be assigned hue and chroma locations in a CIE chromaticity diagram, just like any other colored light source. The changes in the shape and peak energy of the blackbody curves then produce a characteristic color sequence as temperature increases, which results in a curved line called the blackbody locus (Figure 42).

Most depictions of the locus start at the deep red at low temperatures (~1000 °K) and range up and to the left through orange, yellow, white, and bluish white at very high temperatures (>20,000 °K) (see *Color temperature* section). The relationship between the color temperatures of blackbodies and the chromaticity diagram can be expounded upon by the following:

Once a body is heated to when it first begins to glow with a reddish color, then as the temperature of the body increases, it emits visible light at higher and higher frequencies (shorter and shorter wavelengths)¹⁰²...but also continues to emit at the longer (redder) wavelengths. Consequently, when it first starts to emit visible light, almost all of the visible radiation is red, so the object appears to be a very pure red color. As the shorter wavelength emissions are added, the perceived color moves through the orange and yellow hues, but is also become less saturated— because the emission extends on over a broader range of visible wavelengths. As the body begins to emit wavelengths corresponding to green and blue wavelengths, the continued emission of longer wavelengths results in the perceived color moving toward the white region. Eventually, the object becomes so hot that there can be no additional contribution within the visible region – it is emitting light reasonably uniformly across this full visible spectrum, and the “color” stabilizes at a fairly bluish white.

Many chromaticity diagrams present the Planckian locus as the coordinates of blackbody radiators over the range of approximately 1000 °K to 20,000+ °K; while some extend the range to infinity, hence the label of the ∞ (infinity) symbol at the left most end point of the curve (Figure 42, middle). The x,y coordinates of this infinity point are approximately (0.242, 0.240) (Petluri, Raghuram, & Pickard, 2017). Occasionally, although not labeled on any diagrams in this paper, the portion of the Planckian locus extending below approximately 1000 °K (i.e., the area beneath the colored region of the diagram) will be referred to as “Black,” as the blackbody energy is in the IR, which is invisible to the human eye (Nassau, 1983).

¹⁰² The classic analogy is what happens to a piece of iron heated in a blacksmith’s forge.

Caution should be exercised when associating color names with blackbody temperatures, as there is considerable range in the color characterizations with very indeterminate cut-off values. However, for illustrative purposes, Table 4 provides one example of a visible color-blackbody association scheme. Figure 43 is a logarithmic scale plot of hues on the Planckian locus from approximately 800 °K to 57,000 °K (Bhutajata, 2017). A simple comparison between Table 4 and Figure 42 highlights the ineffectiveness of assigning color names to these blackbody temperature values. However, this naming issue should not be confused with display device representations of associated blackbody temperature colors.

Table 4. Representative visible colors associated with blackbody absolute (°K) temperatures.

Blackbody temperature	Visible color name	Peak wavelength (nm)	RGB values
1,000 °K	Deep red	2898	255,56,0
1,500 °K	Reddish orange	1932	255,108,0
2,000 °K	Yellowish orange	1449	255,137,18
3,000 °K	Yellow	966	255,180,107
3,500 °K	Yellowish white	828	255,196,137
4,500 °K	Warm white	644	255,219,186
5,000 °K	White	580	255,228,206
6,000 °K	Bluish white	483	255,247,239
7,000 °K	Dazzling bluish-white	414	243,242,255

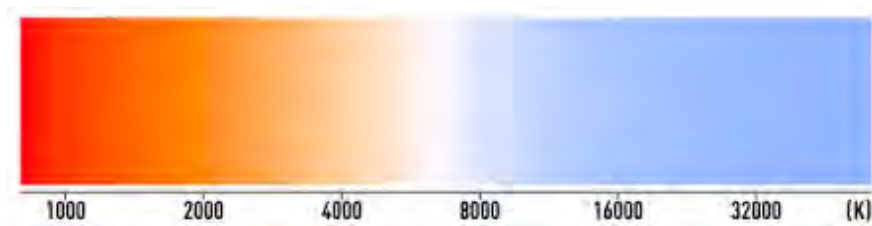


Figure 43. Hues of the Planckian locus from approximately 800 °K to 57,000 °K on a logarithmic scale, based on the same conditions as in Table 4 (Bhutajata, 2017).

In Table 4, the blackbody temperature colors and peak wavelengths (based on Wein’s law) are “named” and visually represented (in the last column) using RGB values generated by a number of different blackbody temperature-RGB conversion calculators found on various major university websites. While variations in RGB values for a given blackbody temperature did arise, they were <1%. However, minor appearance differences were noticeable in presentation boxes displaying the colors for a selected blackbody temperature (e.g., a bluish tint was first noticed at approximately 6750 °K using one conversion calculator but was not noticed using another calculator until 6895 °K). These differences were based only on author observations; nonetheless, the presentation in Table 4 and viewed on a monitor calibrated to sRGB color space with a D65 white point and 2.2 gamma¹⁰³ did not present any blue content at the two highest temperatures even though the naming association scheme presented made such an implication.

¹⁰³ Gamma is measure of the amount of contrast found in an image according to the slope of a gradation curve. High contrast (steep curve) has high gamma, and low contrast (shallow curve) has low gamma.

The Planckian locus has a number of useful key characteristics and features that often are overlooked (MacEvoy, 2015):

- The curve is closest to the equal energy white point at a temperature of ~ 5800 °K;
- Above 5000 °K the curve is nearly straight;
- This straight portion is aligned from blue to yellow (approximately 470 to 575 nm);
- Below 4000 °K, the curve arcs sharply into orange and red, and becomes much more saturated, as temperature decreases;
- An equal temperature difference defines a smaller color difference as the blackbody temperature increases; and therefore
- Blackbody radiation never reaches a violet or purple hue:
- At an infinitely high temperature, the blackbody chromaticity has a dominant wavelength of approximately 470 nm.

In Figure 42 (bottom), a series of straight lines can be observed crossing the Planckian locus. These are called lines of constant CCT, where the perceived color most closely resembles that of an ideal blackbody radiator at the same brightness (under specified viewing conditions). Reiterating the major points from the *Color temperature* section above, the SPDs of many natural and artificial light sources have chromaticities that either lie on or very near a particular chromaticity (point) on the Planckian locus, for which the light source's color can simply referred to by its related Planckian color temperature; however, if the chromaticity of a light source does not lie on (or very near) the Planckian locus, a CCT must be used to describe its appearance (Herandez-Andres, Lee, & Romero, 1999).

It should be noted the lines of CCT (isotemperature lines) in Figure 42 (bottom) are at different angles to the locus curve. This results from the CIE 1931 diagram being a non-uniform scale. When the nearest Planckian chromaticity is based on a uniform-chromaticity-scale diagram, the chromaticity points correlated with each Planckian chromaticity fall on straight lines (isotemperature line) normal to the Planckian locus at that Planckian chromaticity (Kelly, 1963). Graphs showing the Planckian locus and the isotemperature lines both in the CIE 1931 (x,y)-diagram and in the CIE 1960 Uniform Color Scale (UCS) (u,v)-diagram as first proposed in 1937 by D. MacAdam¹⁰⁴ are shown in Figure 44. In each depiction, the lines are drawn to indicate the maximum distance from the locus from which the CIE considers the CCT to be valid.

Standard illuminants.

In addition to the blackbody locus curve and lines of CCT found on most CIE diagrams, there also may be present one or more specialized points marked by an alpha-numeric designation, e.g., A, B, C, and D65 (Figure 45). These points show the chromaticity location of “theoretical” light sources, referred to as *standard illuminants*, which have been established by

¹⁰⁴ American Physicist David Lewis MacAdam (1910-1998) made significant contributions to the field of color science. In reference to this note, he proposed a uniform color scale in 1937 that over the decades progressed to the CIE 1960 and 1976 chromaticity spaces.

the CIE for the purpose of allowing comparison of images (luminance and color) under different lighting conditions (International Commission on Illumination, 2006).¹⁰⁵ These standard

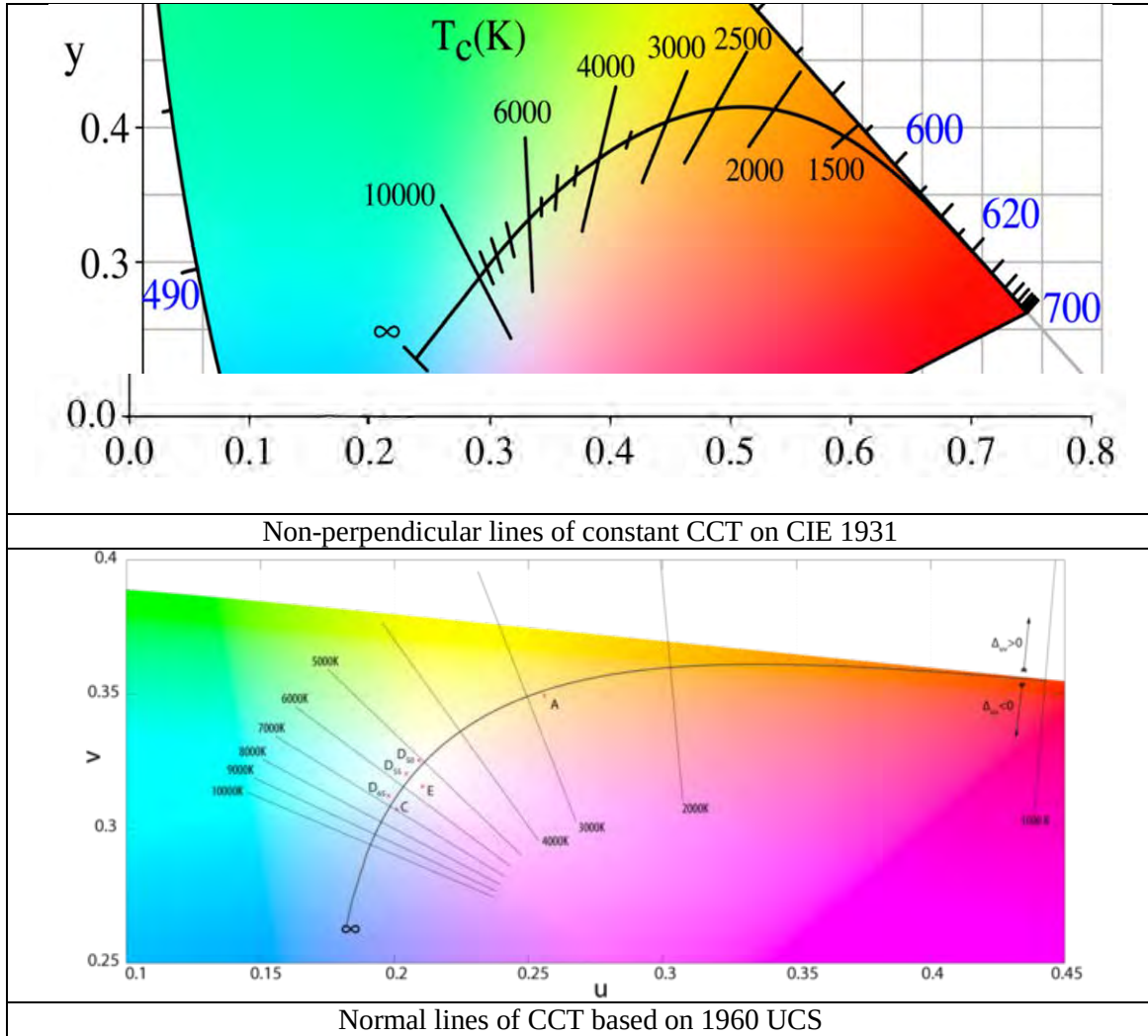


Figure 44. Comparison of lines of constant CCT on CIE 1931 and CIE 1960 UCS.

illuminants are simulated sources of light mathematically presented as plots or tables of values and should not be considered as actual light sources; although several closely mimic real common sources. The most common of these standard and other defined illuminants are summarized in Table 5, with selected relative SPDs shown in Figure 46. Spectra of all of the CIE illuminates can be found in CIE Technical Reports 15:2004, 15:2005, and 15:2006, on Colorimetry (International Commission on Illumination, 2004, 2005, 2006).

There are currently seven series of CIE illuminants. The first three series, illuminants A, B, and C, are all singular points on the diagram and were introduced in 1931 with the intention of representing average incandescent light, direct sunlight, and average daylight, respectively.

¹⁰⁵ Technically, only two illuminants are standardized by the CIE: illuminant A and illuminant D65; the additional CIE illuminants correspond to theoretical sources of tabulated relative spectral power distributions.

The physical simulation of an illuminant is called a light source. Some illuminants (A, B, C, D55, D65 and D75) can be represented by actual light sources; others (such as C) cannot.

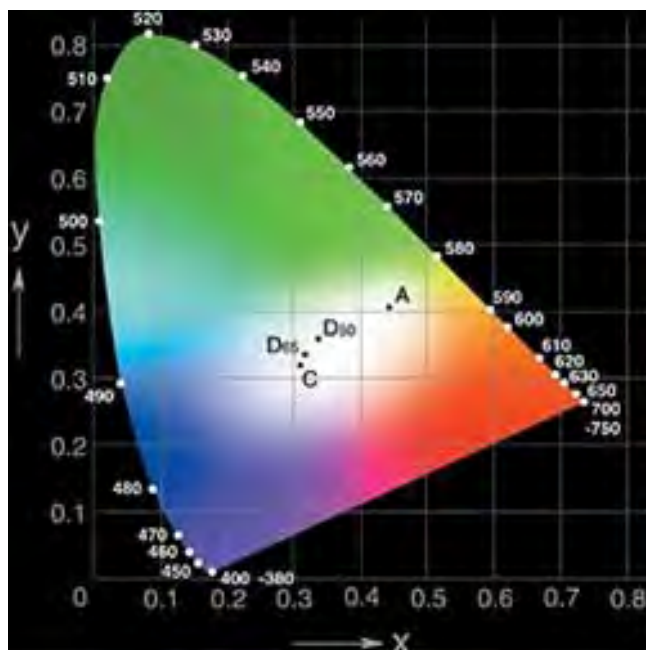


Figure 45. Illuminants plotted on a CIE chromaticity diagram.

Historically (at least for the last century), the most common artificial light source has been the tungsten filament lightbulb. This light source is almost totally dependent on a single variable, filament temperature. Standard illuminant A was defined first in 1931 to represent this type of light source. By definition, illuminant A has the same relative SPD as a Planckian radiator at a temperature of ~ 2856 °K.

Illuminants B and C were defined in 1931 to represent the most commonly occurring natural light source, daylight produced by the Sun. Illuminant B represented noon (direct) sunlight at 4874 °K; illuminant C represented average (shady) daylight (not including its UV region) at 6774 °K.

An issue with illuminants B and C is they have very little power in the UV region (Hunt & Pointer, 2011). While not significant in most situations, it is important in the presence of fluorescence, e.g., fluorescent optical brighteners. This created a need for a standard illuminant more representative of daylight in the UV region. This gave rise, beginning in 1963, to the D series standard illuminants of different CCTs (e.g., D50, D55, D60, D65, D75, and D93).¹⁰⁶ These D illuminants are characterized by their CCTs. The best known and most used of these is D65,¹⁰⁷ which represents average noon daylight in the northern sky at noon and has a CCT of 6504 °K. Most standards and requirements in colorimetry state that D65 should be used in all

¹⁰⁶ D55 and D65 were introduced in 1964; D50 was introduced in 1974 and revised in 1975.

¹⁰⁷ The CCTs of the commonly used illuminants D50, D55 and D65 are slightly different to the values suggested by their names. Due to the revision of an estimate of one of the constants in Planck's law after the standards were defined, the CCTs were adjusted slightly.

colorimetric calculations requiring representative daylight, unless there are specific reasons for using a different illuminant.

Table 5. Summary characteristics of most commonly encountered CIE illuminants (Wyszecki & Stiles, 1982; International Commission on Illumination, 2006; Schanda, 2007; Brainard & Stockman, 2010).

Illuminant designation	Description & CCT	Most common use	1931 CIE coordinates (x,y)	Notes
A	Incandescent/ Tungsten; 2856 °K	Applications of colorimetry with incandescent lighting	(0.44757, 0.40745)	Yellow-red color
B	Daylight; Noon sunlight; 4874 °K	Seldom used; no longer has CIE status of Standard Illuminant	(0.34842, 0.35161)	Derived from illuminant A by using liquid filters
C	Average daylight from the northern sky (not including UV region); 6774 °K	No longer has CIE status of Standard Illuminant	(0.31006, 0.31616)	Derived from illuminant A by using liquid filters
D50	Daylight, horizon (sunrise/sunset) light; 5003 °K	Reference for printing industry and graphic arts	(0.34567, 0.35850)	Represents warm daylight at sunrise or sunset
D55	Daylight, mid-morning or mid-afternoon; 5503 °K	Metamerism testing	(0.3325, 0.3475)	More red-yellow than D65.
D65	Average noon daylight in northern sky at noon (including UV region); 6504 °K	Colorimetric calculations requiring representative daylight; television, sRGB color space	(0.31271, 0.32902)	A bluish light source used in color matching applications of paints, plastics, and other manufacturing
D75	North sky daylight; 7504 °K	Colorimetry, metamerism testing, and evaluation of opaque materials	(0.29902, 0.31485)	—
E	Theoretical equal energy radiator; not a blackbody so it doesn't have a color temperature	Manufacturing colorimetry calculations	(1/3,1/3)	Located beneath the Planckian locus, and roughly isothermal with D55 at 5455 °K

Table 5 (continued). Summary characteristics of most commonly encountered CIE illuminants (Wyszecki & Stiles, 1982; International Commission on Illumination, 2006; Schanda, 2007; Brainard & Stockman, 2010).

Illuminant designation	Description & CCT	Most common use	1931 CIE coordinates (x,y)	Notes
F1	Two semi-broadband emissions; 6430 °K	Typical office illumination	(0.31310, 0.33727)	Daylight fluorescent lamp
F2	Two semi-broadband emissions; 4230 °K	Typical office illumination; the most commonly used fluorescent illuminant	(0.37028, 0.37529)	Cool white fluorescent (CWF)
F3	Two semi-broadband emissions; 3450 °K	–	(0.40910, 0.39430)	White fluorescent lamp
F4	Two semi-broadband emissions; 2940 °K	Used for calibrating the CIE color rendering index (CRI)	(0.44018, 0.40329)	Warm white fluorescent lamp
F5	Two semi-broadband emissions; 6350 °K	–	(0.31379, 0.34531)	Daylight fluorescent lamp
F6	Two semi-broadband emissions; 4150 °K	–	(0.37790, 0.38835)	Lite white fluorescent lamp
F7	Daylight fluorescent; broad-band lamp; 6500 °K	D65 daylight simulator; and colorimetry	(0.31292, 0.32933)	Flatter and wider range spectral power distribution than F1-6
F8	Daylight fluorescent; broad-band lamp; 5000 °K	D50 daylight simulator	(0.34588, 0.35875)	Flatter and wider range SPD than F1-6
F9	Cool white deluxe; broad-band fluorescent lamp; 4150 °K	–	(0.37417, 0.37281)	Flatter and wider range SPD than F1-6

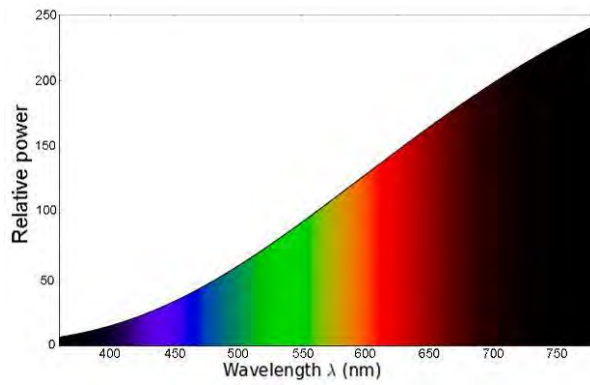
Table 5 (continued). Summary characteristics of most commonly encountered CIE illuminants (Wyszecki & Stiles, 1982; International Commission on Illumination, 2006; Schanda, 2007; Brainard & Stockman, 2010).

Illuminant designation	Description & CCT	Most common use	1931 CIE coordinates (x,y)	Notes
F10	Broad-band fluorescent lamp; 5000 °K	–	(0.34609, 0.35986)	Also known as TL85
F11	Fluorescent narrow tri-band lamp; 4000 °K	Warehouse lighting and colorimetry	(0.38052, 0.37713)	Also known as TL84
F12	Fluorescent lamp; 3000 °K	–	(0.43695, 0.40441)	Also known as TL83
HP1	High-pressure (HP) sodium vapor lamp	Lighting engineering	(0.5330, 0.4150)	Yellowish
HP2	Color enhanced high-pressure (HP) sodium lamp	Lighting engineering	(0.4778, 0.4158)	–
HP3	High-pressure (HP) metal halide lamp	Lighting engineering	(0.4302, 0.4075)	–
HP4	High-pressure (HP) metal halide lamp	Lighting engineering	(0.3812, 0.3797)	–
HP5	High-pressure (HP) metal halide lamp	Lighting engineering	(0.3776, 0.3713)	–
L	LED	Multiple lighting applications	–	Under consideration

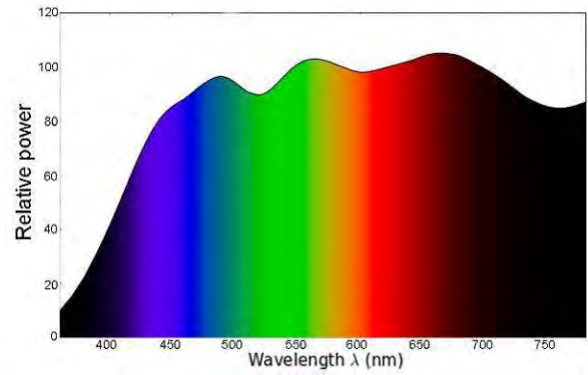
CIE illuminant E is a theoretical reference radiator. All wavelengths in illuminant E are weighted equally with a relative spectral power of 100. Since it is not a Planckian radiator, no color temperature is given, however it can be approximated by a CIE D illuminant with a correlated color temperature of 5455 °K. On the CIE 1931 chromaticity diagram, it is located beneath the Planckian locus, and is roughly isothermal with D55 (see Figure 44, p. 58). It is used in lighting manufacturing for colorimetry calculations (Philips Lumileds Lighting Company, 2006).

The F series is CIE proposed but not standardized in the official sense (Choudhury, 2014). It consists of 12 fluorescent lamp types, F1-F12, each being different in the combinations of gases used and phosphors used as coatings for the lamp tubes. Among these, F3 and F12 are most commonly used in the industry and are the most important for colorimetric evaluations. These 12 illuminates are divided into three groups according to their spectra (Oleari, 2016):

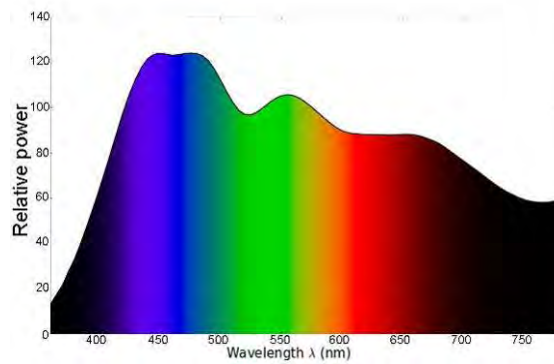
- (1) Normal or standard – F1-F6, where cool white F2 is the most representative and F4 is used for calibrating the CIE color rendering index (CRI) (see *Color rendering* section)
- (2) Broadband – F7-F9, where daylight fluorescent F7 is the most representative; and
- (3) Three narrow bands – F10-F12, where white fluorescent F11 is the most representative.



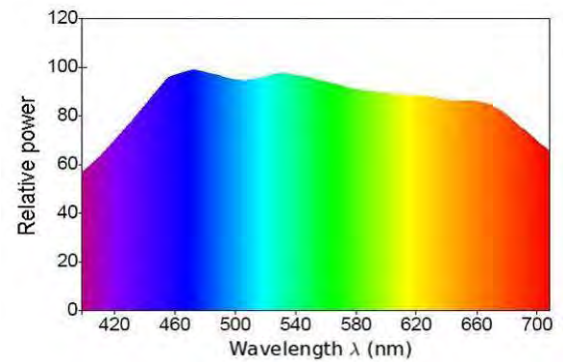
Illuminant A



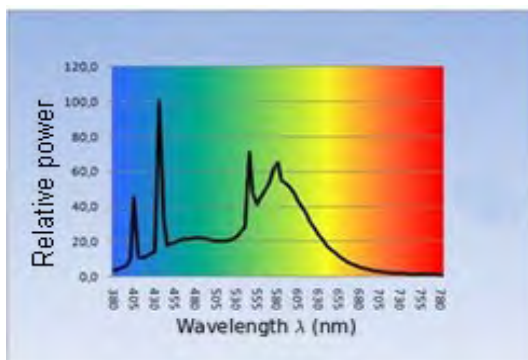
Illuminant B



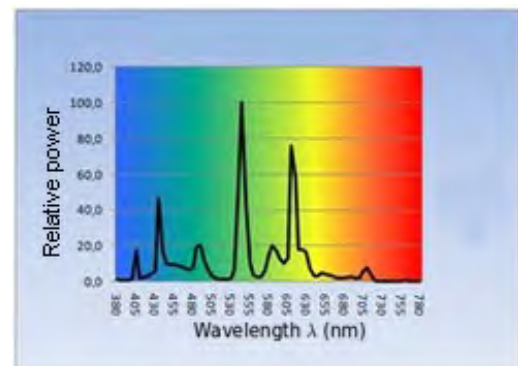
Illuminant C



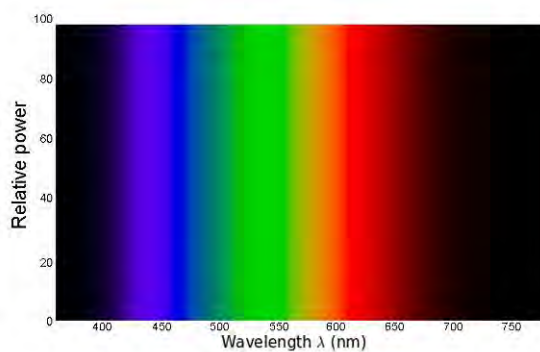
Illuminant D65



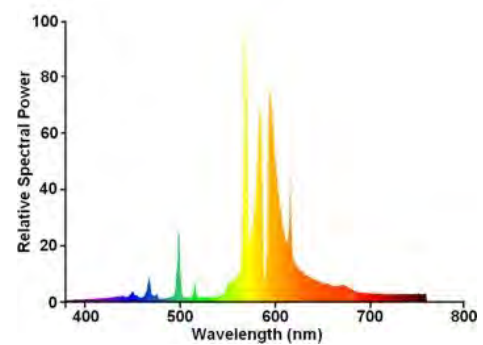
Illuminant F2



Illuminant F11



Illuminant E



High-pressure (HP) Sodium

Figure 46. SPDs for various CIE defined illuminants.

In 2005, the CIE 15:2005 Colorimetry technical report provided an expanded set of Series F fluorescent illuminants. These are denoted by the nomenclature of FL3,k,k, where k is 1-14, and are defined by chemical composition and the number and type of bands in their SPDs. As examples, FL3.7 to FL3.11 consists of three-band fluorescents, and FL3.15 is a D65 simulator.

There also are five high-pressure lamps designated as HP1-5, of which two are sodium vapor lamps and three metal halide lamps; these are normally not significant in colorimetry but rather in lighting engineering (Klein, 2010). Illuminant HP1 is a sodium vapor lamp that emits pale yellow light, due to its two closely spaced visible wavelengths of 589.0 and 589.6 nm. Illuminant HP2 is a color enhanced sodium vapor lamp. Illuminants HP3-5 are metal halide lamps.

Two light sources of increasing importance are lasers and LEDs. It is expected that a CIE series standard illuminate will be developed for these sources. A test method for LED lamps and light sources was presented at the CIE 2017 Midterm Meeting (International Commission on Illumination, 2017). It was reported that an L series illuminant for LEDs has already been proposed as CIE Draft International Standard (DIS) 015/E:2014 (International Commission on Illumination, 2014). Photometric and colorimetric quantities covered in this standard include total luminous flux, luminous efficacy, partial luminous flux, luminous intensity distribution, center-beam intensity, luminance and luminance distribution, chromaticity coordinates, CCT, CRI, and angular color uniformity. This standard does not cover LED packages and products based on OLEDs.

Developing a typical LED SPD to use as a standard has been a challenge, as LED technology has been changing so rapidly, particularly with the advent of white LEDs. Further complicating the effort has been the considerable variation in LED lamps and outputs among different manufacturers (Hunter Associates Laboratory, Inc., 2015).

Solid-state lighting based on lasers has offered even a greater challenge to the adoption of an illuminant standard. Light emitted from lasers, while offering high efficiency, has even a narrower spectral linewidth than light emitted from LEDs or phosphors. Therefore, it has been generally believed white light produced by a combination of lasers of different colors would not be of high enough quality for producing acceptable general illumination. An RGB (red-green-blue) or RYGB (red-yellow-green-blue) white light source composed of three or four discrete laser lines falls far short of covering the visible spectrum, and it has not been repeatedly demonstrated either would properly render the colors of objects in typical environments (see *Color rendering* section) (Ohno, 2005).

Nonetheless, Neumann et al. (2011) have argued the reflectance spectra of most common objects, both natural and man-made, are broad, smooth, and continuous (Maloney, 1986). Therefore, some multi-source light, provided the narrow band light sources are not too widely spaced in wavelength, will be differentially reflected off object surfaces with such spectrally broad reflectance. Their research has showed at least one 4-color RYGB laser configuration was, in terms of color rendering quality, capable of serving as a white illuminant nearly indistinguishable from high-quality reference illuminants that included an incandescent lamp and three white LED types.

Color rendering.

When choosing which illuminant to use when measuring or evaluating a sample's color spectra, its point of use/viewing conditions must be considered. Once determined, this illuminant should be used as the standard for all future evaluations to maintain color consistency, accuracy, and efficiency. At the heart of this requirement with regards to illuminants is the concept of what defines the ability of a light source (illuminant) to ensure good color fidelity. In 1947, the Dutch scientist P. J. Bouma described the features that would define such a source. He noted a source with good-color-rendering properties, in daylight or artificial light, should reveal a full range of colors (hue, lightness, and saturation), should enable good color discrimination¹⁰⁸ between objects of similar spectral reflectance, and should not distort colors (Bouma, 1971).

While of great interest in the retail and advertising industries, and hence the commercial lighting industry, where product appearance is critical, this issue is also important to the aviation community where consistent color is required in the cockpit for color recognition and discrimination tasks.

The most common and long employed metric for describing the color rendering quality of light sources is the Color Rendering Index (CRI).¹⁰⁹ The CRI is a scale from 0 to 100%¹¹⁰ indicating how accurate a selected light source is at rendering color when compared to a “reference” light source – the higher the CRI, the better the color rendering ability.¹¹¹ In Figure 47, a “red” apple is presented as would be seen when viewed under different lighting sources of 2700 °K CCT with decreasing (right to left) CRI values.

The CRI is a method devised by the International Commission on Illumination (1995), setting best possible rendering of colors at 100% and the very poorest rendering at 0%. The CRI (R_a) score is an average value based on eight unsaturated (sometimes referred to as pastel) test colors (R1-R8) presented in Figure 48. Specifically, the CRI is calculated from the differences in the chromaticities of eight 1995 CIE color space standard color samples when illuminated by a test light source and by a reference illuminant of the same CCT; the smaller the average difference in chromaticities between illuminants, the higher the CRI value. Lower CRI values indicate that some colors may appear unnatural when illuminated by the test source lamp.



Figure 47. Viewing a “red” apple illuminated by light sources of decreasing CRI.

¹⁰⁸ *Color discrimination* is the ability to differentiate between shades of a color or the difference between two or more colors when luminance has been equated.

¹⁰⁹ The *Color Rendering Index* (CRI) also is referred to as the Color Rendition Index; internationally, the symbol CRI R_a is used.

¹¹⁰ While adopted herein by convention, there is some disagreement in the literature as to whether the CRI should be expressed as a percent value.

¹¹¹ The CRI definition allows negative numbers, generally rounded up in literature to zero (Wood, 2010); an example is a low pressure sodium lamp (e.g., streetlight) with a CRI = -47%.



Figure 48. Test colors used in calculating CRI.

To be considered an excellent illuminant for color assessments, its CRI shouldn't be less than 90% (Sergeev, Tarasov, Arapov, & Arapova, 2015). A CRI of 80% or above typically is considered most desirable for indoor lighting applications. A useful, but somewhat arbitrary, definition of illuminant CRI quality is provided in Table 6. The Sun as a source, at least direct sunlight, has a CRI value of 100%. Tungsten halogen incandescent lamps have CRI values of 95% or higher. A representative list of CRI values for common illuminants is provided in Table 7.

Table 6. CRI quality classes.

CRI range (%)	Quality rating
>90	Excellent
80-90	Very good
70-80	Good
60-70	Marginal
40-60	Poor
<40	Very poor

The CRI is used universally in industry to measure color quality in finished products. However, it does have limitations (Erdmann, 2010; Liao, 2014). For example, the CRI does not correlate well with the ability to discriminate among objects with slight differences in spectral reflectances (Figueiro, Appleman, Bullough, & Rea, 2006). In addition, it is important to realize that the CRI is a metric of fidelity not of aesthetic satisfaction, which is more complex and subjective (Dangol et al., 2013; Freyssinier & Rea, 2013). Furthermore, this index is based on a very small number (eight) of color samples, which are unsaturated. The CRI does not reasonably characterize highly structured, narrowband spectral emissions like those from solid-state light sources,¹¹² especially LEDs with red, green, and blue components, which may increase or decrease saturation of certain colors. Such is the case with multiple-chip white LED lights, which have poor CRI values, often as low as 20%. The reason for such poor scores is that the SPDs of RGB LEDs exhibit spikes that correspond to the output of the three LEDs, with few other wavelengths. In practice, LED lights that have high CRI values do not necessarily render colors naturally, while LEDs with low CRI values can produce a more realistic appearance. The CRI

¹¹² Generally, light sources with smooth SPDs have high CRI values, and light sources with spikes or jagged features in their SPDs have lower CRI values. However, well-designed SPDs may be able to have sharp features and still produce acceptable CRI values (Houser, Mossman, Smet, & Whitehead, 2015).

also penalizes a light source intended to produce enhanced color contrast but does not compensate for illumination level. This is important due to the Hunt effect that states the more brightly illuminated an object or scene is, the more colorful it is perceived to be (Hunt, 2004; Hurkman, 2013). In addition, it can be argued that a single number cannot fully characterize the multidimensional experience of color such as color appearance, color fidelity, chromatic discrimination, vividness, and observer preferences (Dangol et al., 2013).

Table 7. CRI values for common illuminants, including CIE-defined.

Illuminant	CRI (%)
Sun (Direct sunlight)	100
Candle flame	100
Tungsten halogen incandescent lamp (CCT 3190 °K)	>95
Illuminant A	100
D65	94
F1	76
F2	60
F3	57
F4	51
F5	72
F6	59
F7	90
F8	95
F9	90
F10	81
F11	83
F12	83
HP1-2 (High-pressure sodium)	8-22
HP3-5 (High-pressure metal halide)	74-85
LED	80-98

Several new metrics have been proposed and developed to replace or supplement the CRI. Houser, Wei, David, Krames, & Shen (2013) identified 22 indices in a review of measures for light source color rendition in the literature. They classified the indices into three basic classes of color rendition: the accurate rendition of colors so they appear as they would under familiar reference illuminants; the rendition of objects such that they appear pleasant, vivid, or flattering; and the capability of an illuminant to allow an observer to distinguish between colors when viewed simultaneously. These dimensions of color rendition are respectively referred to as: color fidelity, color preference, and color discrimination (Bouma, 1948; Schanda, 1985).

One of the most notable of these indices is the Color Quality Scale (CQS) developed by the National Institute of Standards and Technology (NIST) in 2006 (Davis & Ohno, 2010). The CQS was designed to resolve the problems of the CRI, while maintaining consistency with the CRI's scores for existing lamp products. The CQS was intended to eventually replace the CRI and to be effective for both traditional and solid-state lighting technologies. It differs mainly from the CRI by taking into account observer subjective color saturation perception. The CQS

involves several features of color quality, including: color rendering, chromatic discrimination, and observer preferences.

The method for calculating the CQS is derived from modifications to the CRI method. The CQS, like the CRI, is a test-sample based method, i.e., color differences in a uniform object color space are calculated for a predetermined set of reflective samples when illuminated by the test source and a reference illuminant. Where the CRI is based on only eight reflective samples of low to medium chromatic saturation, the CQS uses 15 Munsell samples in its calculations (Figure 49). Additionally, the computation scheme for determining the CQS (Q_a) color rendering score differentiates between hue and saturation shifts and takes the directions of the shifts into account. The CQS uses the CIELAB color space rather than the CIE 1964 UCS used in the CRI.¹¹³ To ensure that large shifts of any color are adequately reflected in the score, color differences are combined with a root-mean-square (RMS). Finally, an appropriate scaling factor is chosen to produce a CQS score range of 0-100 (Davis & Ohno, 2010). Table 8 gives a comparison of CRI and CQS values for a few selected light sources. Note there is little difference in the two metrics for broad band sources. In contrast, in three of the sample RGB LEDs, the CQS score is somewhat higher than the CRI score. However, this is not always the case, as with the RGB LED 4 sample, which has a higher CRI score.



Figure 49. The color test samples used for the CQS metric.

Table 8. A comparison of CRI and CQS scores for selected light sources (Davis & Ohno, 2010).

Lamp	CCT	CRI (%)	CQS
Incandescent	2812 °K	100	98
Cool white fluorescent	4196 °K	59	61
Mercury	3725 °K	53	53
Metal halide	4167 °K	92	92
RGB LED 1	3018 °K	31	55
RGB LED 2	3300 °K	59	78
RGB LED 3	3300 °K	73	79
RGB LED 4	3304 °K	85	77

Another noteworthy color rendering metric is the Gamut Area Index (GAI). This is not a new metric as its basic concept was developed by W. A. Thornton over 45 years ago (Thornton, 1972; Rea, 2010). He proposed gamut area¹¹⁴ (GA) as a measure of color rendering. GA is defined as the area enclosed within three or more chromaticity coordinates in a given color space. Rather than consider the shift in chromaticity of the eight CIE standard color samples, Thornton was interested in the separation of their chromaticities with the belief that the greater the separation, the greater the saturation (vividness) of colors. He also confirmed the greater the separation, the greater the ability to discriminate between object colors, which is another

¹¹³ The CRI uses the 1964 CIE (U^* , V^* , W^*) color space, also known as the CIEUVW, which is based on the more familiar CIE 1960 UCS.

¹¹⁴ Gamut used here is the same as in reference to a range of colors.

measure of color rendering. Thus, the greater the separation of the eight standard samples, the greater the GA created by the light source.

The GAI is calculated from the area of the polygon defined by the chromaticities of the eight CIE standard color samples (R1-R8) in CIE 1995 color space (Technical Report No. 13.3-1995) for the CRI when illuminated by a given light source (Boyce 2003). In general, the larger the GAI, the more saturated the object colors will appear. Until the search for other color rendering indices, the GAI was more commonly used in Japan than in North America.

As previously stated, the GAI for any selected source is calculated from the area of the polygon defined by the chromaticity of the eight color samples used for the CRI in the CIE u',v' color space. An equal energy spectrum was arbitrarily assigned a GAI value of 100, and the GA of all other light sources is scaled accordingly to derive their corresponding GAI. Given this definition, GAI values greater than 100 are possible. A high GAI is characteristic of a source with good color discrimination and saturation of colors (vividness). When a GAI value is over 100, it usually means colors appear oversaturated, and observer's preference declines. Table 9 gives a comparison of CRI and GAI values for a few selected light sources. Figure 50 shows the GAs of various illuminants, bounded by the eight sample (R1-R8) chromaticities used to calculate the GAI and CRI (Guo & Houser, 2004).

Table 9. A comparison of CRI and GAI values for selected light sources (Freyssinier & Rea, 2010).

Light source	CCT	CRI (%)	GAI
T8 fluorescent	6369 °K	85	96
Xenon	5853 °K	97	91
White PC LED*	5097 °K	95	99
RGB LED	4000 °K	89	82
Metallic halide	4197 °K	92	83
CIE D50	5003 °K	100	88
CIE D65	6504 °K	100	98

*Phosphor-converted LED. Most white LEDs are manufactured as a phosphor-conversion type, consisting of a GaN/InGaN-based blue LED and a yellow phosphor excited by a blue LED (Ryn, 2013).

The GAI has the same goal as CQS, which is giving more weight to subjective perceptions of vividness and natural quality. Since they use different metric methods, the GAI is intended to be used with CRI (not as a replacement), an idea explored below. However, the GAI has the same weakness as the CRI; both use the same small, desaturated (pastel) color sample set (Lighting Passport, 2015). Another problem is objects illuminated by a source with a greater GA may now appear overly saturated and hence unnatural. As has been pointed out, inherently, the GAI and CRI are opposite in their purpose: one metric emphasizes the stability of colors with respect to familiar light sources, while the other metric is sensitive to the saturation of colors (Alliance for Solid-State Illumination Systems and Technologies, 2010).

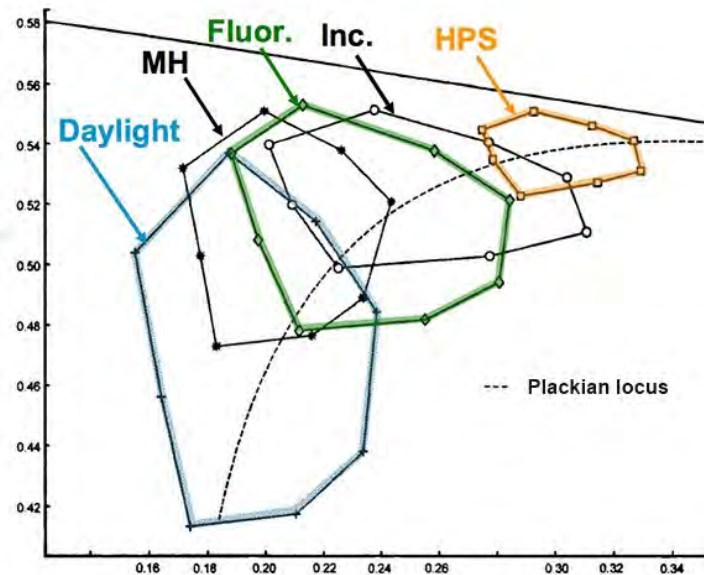


Figure 50. The GAs of selected light sources, bounded by the R1-R8 sample chromaticities used to calculate the GAI and CRI (adapted from Thornton, 1972; Boyce, 2003).

A third possible replacement color rendering quality index is the *Full-Spectrum Index* (FSI). The FSI is a mathematical measure of how much a light source's spectrum deviates from an equal-energy spectrum (National Lighting Product Information Program [NLPPI], 2003). An equal-energy spectrum is a theoretical spectrum that provides the same radiant power at all wavelengths (i.e., a "full" spectrum). Therefore, for humans to see the full and correct colors of an object, the light source must generate light across the full visible spectrum. Subtle differences in the perceived colors of objects arise from slight differences in the spectral reflectance of those objects. If a light source does not provide radiant power at those wavelengths where the spectral reflectances of those objects differ slightly, the objects will appear to have the same color. Therefore, a lamp that emits radiant power at all visible wavelengths would be expected to have excellent color rendering properties.

The FSI is based on the sums of the squared deviations between the cumulative SPDs of the test light source and the reference equal energy source. In order that any spikes or dips in the SPD be weighted equally no matter where along the spectrum they occur, the squared deviation is calculated 351 times (in 1-nm increments between 380-730 nm, inclusive), and the values are averaged to produce the FSI. The lower the FSI value the more "full" the spectrum, with zero being an equal energy spectrum. Table 10 compares typical CRI and FSI values for representative commercially-available light sources. An additional mathematical transformation performed on the FSI produces the metric known as the *Full Spectrum Color Index* (FSCI), using an inverse scale from 0 to 100, which is directly comparable to the CRI. An equal energy spectrum has an FSCI value of 100; a standard "warm white" fluorescent lamp has an FSCI value of 50; and a monochromatic light source (e.g., low-pressure sodium) has an FSCI value of 0.

Table 10. A comparison of CRI and FSI values for selected light sources (NLPIP, 2013).

Light source	CCT	CRI (%)	FSI
Equal energy spectrum	5457 °K	95	0
Daylight	5500 °K	100	0.35
Daylight	11,000 °K	100	2.0
Incandescent	2800 °K	100	5.3
T8 fluorescent	3300 °K	84	92
Xenon (1000 watt)	5900 °K	96	1.2
White LED	5000 °K	78	5.2
RGB LED (615 nm/525 nm/470 nm)	4400 °K	65	9.8
RGB LED (640 nm/525 nm/470 nm)	4200 °K	26	8.2
Metallic halide	3600 °K	68	5.0
Low-pressure sodium	1800 °K	0	52
High-pressure sodium	2000 °K	12	22

In practice, the four color rendering quality metrics discussed above (CRI, CQS, GAI, and FCI) can at times seem to contradict each other (NLPIP, 2003). For example, an incandescent lamp has the highest possible CRI value of 100, but scores poorly on FSI because it is deficient in the short wavelength range. A study of color naming accuracy found CRI to be a poor predictor and GAI to be a good predictor color rendering quality (Deng, 2001). In another study, light sources with high values on GAI and low values on CRI were highly rated in terms of color preference (Narendran & Deng, 2002). In general, a high CRI implies that colors will appear natural when viewed under a light source; a high FSCI (low FSI) implies the light source will provide good discrimination between small color variations; and a large GAI implies colors will be highly saturated (Narendran & Deng, 2002; Boyce, 2003).

Given these frequent conflicts, the growing dissatisfaction with the traditional CRI when applied to solid-state light sources, and the proposal for other color rendering quality metrics, a number of color researchers and lighting experts have suggested the use of a combination of these metrics (Alliance for Solid-State Illumination Systems and Technologies, 2010; Rea, 2010; Houser, Wei, David, Krames, & Shen, 2013).

Freyssinier & Rea (2010) proposed a two-metric system combining the CRI, a measure of color consistency with respect to a reference source, with the GAI, a measure of color saturation. When used together, the two metrics seem to optimize the color appearance of natural objects like fruits and vegetables, enhancing their vividness without making them appear unnatural and their use in commercial lighting applications (e.g., architectural and advertising applications) (Rea, 2010). They were able to demonstrate when used in conjunction with one another, sources with high CRI values and moderately high values of GAI tend to be preferred over light sources having high values of only one measure (Rea & Freyssinier, 2010).

Retail lighting experts historically have used two light source metrics to define color properties for their application: CCT and the CRI (Lighting Resource Center, 2010). CCT was used as an indication of the apparent “warmth” or “coolness” of the light emitted by a source,

and the CRI was used as an indication of the light source's ability to make objects appear natural. However, recently, the retail industry has been moving to the same two-metric system described above, continuing to rely on the well-known CRI but adding the GAI to enhance color vividness. While application driven, in general, a light source with a color temperature in the 5000-5500 °K range, with a CRI value of 90% or greater, will provide highly acceptable color rendition.

Even without the impetus provided by the rise in solid-state lighting technologies, it has been suggested at least two single-number metrics be used to obtain a reasonably accurate color quality rendering assessment of a light source (Guo & Houser, 2004; Smet, Ryckaert, Pointer, Deconinck, & Hanselaer, 2010; Boyce, 2014). This would include a relative metric such as the CRI or CQS and an absolute metric (i.e., without a reference source) such as the GAI. To ensure a good lighting design, designers should choose sources with both high CRI and GAI values. The combination of naturalness provided by a high CRI and vividness provided by a high GAI would ensure high viewer satisfaction for warm and cool sources, both at high and low levels of illumination, for either general illumination or accent lighting. The NLRIP has suggested lighting specifiers will become more likely to "triangulate" to the most useful light source for a particular color application, making use of several color indices (Narendran & Deng, 2002).

The level of color rendering needed does vary with application. Street and warehouse lighting do not require high rendering values. However, better color rendering, in general, makes objects appear more similar to viewers' expectations and can increase comfort and satisfaction levels. Face-to-face interactions with people, handling of food, illumination of living spaces, reading and detail work, and all activities involving color selection or design will certainly benefit from better color rendering (Houser, Mossman, Smet, & Whitehead, 2015).

The concern of color rendering under varying light sources is not confined to retail and advertising applications. It was a major problem in the development of color aeronautical charts and maps in the early decades of aviation (see *Evolution of aeronautical charts and maps* section); it is an issue with illuminated displays; and to some extent is applicable to color recognition in cockpit displays, which must be viewed under a variety of illumination conditions.

White and black points.

Of particular note in the chromaticity diagram depictions in Figures 32 (left), 34 (left), 40, 41g-h, 42, and 45 is a central region having the appearance of white (see *Color questions* section). The implication is there is no single white. The closest thing to a single white is the equal energy white, E (Figure 41 h, p. 53). It is defined as the x,y coordinate of a SPD having equal intensity or energy at every wavelength in the visible spectrum. The CIE 1931 color matching functions are each normalized so their integrals over the visible spectrum are all equal. This means the tristimulus values for equal energy white (E) will all be equal (i.e., $X = Y = Z$), which results in coordinates of $x = y = 1/3$. Equal energy sources do not occur in nature and would be prohibitively expensive to create artificially (Kelly, 2012).

In the above discussions, several references were made to the *white point* of a color space or illuminant. The white point is important because it provides the relative weight of the R, G,

and B components. One example is the point in Figure 33 (p. 46), a RGB color space where the values of R, G, and B are equal to 255 at the point (255,255,255). Formally, such white points in all color spaces are defined as a set of tristimulus values or chromaticity coordinates, serving as a reference point to define "white" in image capture, encoding, or reproduction (Kennel, 2007). The three primaries and the white point completely specify a RGB color space. A gamma correction curve (See *Gamma correction* section below) also is necessary to compensate for the non-linearity of displays, but it's not strictly part of the model.

Another obvious characteristic of a white point is its position in the color space is where color saturation is zero (Jahne, 2004). As for any two chromaticity points, if a line is drawn from the white point to any pure spectral color boundary point, the line is of constant hue with each point on the line representing the result of mixing white with the hue, i.e., a tint (see *Color properties* section). From the white point to the pure hue, the saturation increases linearly.

Moving from color theory into real-world operational color systems, the white point value is never perfectly white and requires measurement (Krig, 2016). The human eye easily adapts to different tints in the color of light, just as it does to different levels of illumination. A non-luminous object (such as a sheet of paper) is objectively agreed to be "white" if it reflects all colors (visible wavelengths) approximately equally, which means it takes on the color appearance of the ambient illumination (Steer, 2012). However, except for critical color tasks (e.g., photography and color graphics), most individuals simply accept illumination from regular filament lightbulbs, sunlight (under varying conditions), and even fluorescent light as being white. Colors that are generally accepted as being white are usually close to the color of black bodies of approximately 2500 °K or higher.¹¹⁵ Therefore, "whites" for color-critical tasks are often specified in terms of a color temperature. For example, illuminant D65 (6504 °K) is the white point used in sRGB, the most common RGB standard. It has the coordinates of $x = 0.3127$, $y = 0.3290$).

This D65 white point has a very practical application in the calibration of a display, as it affects the appearance of white on the display. As previously stated, there is no such thing as pure white; therefore, every light source has a slight hue or color cast to it. Any white objects that appear on display will have a slight color cast. This mostly goes unnoticed; as with the sheet of paper mentioned above, a blank display screen is perceived as being a "pure" white. However, if the color temperature of the display is changed, a dramatic difference (with a color cast) will become obvious (Perkins, 2012).

A frequently missing element of most color spaces is a well-defined definition of a "black point" (Lianza, 2011).¹¹⁶ The black point is the darkest pixel in the image. In the RGB color space, this point is defined as (0,0,0). Where the white point is concerned mostly with the *color* of white, the black point is concerned more with the *density* of black (Fraser, Murphy, & Bunting, 2004). The importance of the white point color lies in the tendency of the human visual system to use the color of the white in a scene or image as the reference for all other colors.

¹¹⁵ Light bulbs frequently are characterized as Soft White (2700-3000 °K), Bright White/Cool White (3500-4100 °K), and Daylight (5000-6500 °K). The higher the color temperature in °K, the "whiter" the color temperature.

¹¹⁶ One exception is the Adobe RGB color space (described in this section).

However, the density of the black is what is used to determine one limit of the dynamic range¹¹⁷ of a scene or image. The larger the dynamic range, the greater the ability to render detail.

This does not imply white only has color and black only has density, as both white and black have color and density. It implies only that color is the more important characteristic of the white (point), and density is the more important characteristic of the black (point). This principle is demonstrated in CMYK printers, where black ink (K) is added to the C, M, and Y inks in order to produce a denser (darker) black.

As color information in a scene is converted into an image file and is passed from one device (color space) to another (see *Color management* section), it is important the black point in the original source be translated correctly in each step. If this fails to happen, then two outcomes, both undesirable, may occur (Fraser, Murphy, & Bunting, 2004):

- (1) If the source black point is lower than of the destination, values in the source darker than the destination black point will be clipped, losing shadow detail.
- (2) If the source black point is higher than of the destination, the conversion will not contain true blacks, producing a washed out result.

As a practical example, RGB images often contain colors darker than the darkest color a printer can reproduce. As a consequence, in the printed image, some details in the shadows may be lost (Mestha & Dianat, 2009).

A solution to this problem is known as *Black Point Compensation* (BPC) (International Color Consortium [ICC], 2010). BPC is a technique to make adjustments between the maximum black levels of source image data (files) and the black capabilities of various processing and output devices. Many imaging software programs provide BPC capability to address color conversion problems caused by differences between black points of various device profiles (Adobe Systems, 2006).

In summary, the white and black points are two important points in defining a color space. They can be thought of as anchor points in a color space (Dillard, 2009). Figure 51 depicts a RGB color space, labeling the white and black points. The line connecting the black and white points is known as the neutral axis (gray scale intensity).

These two points are also two very important calibrations for displays. When the black point is properly set, an RGB value of #000000 or (0,0,0) will appear as true black on a display. In the test pattern in Figure 52 (left), four distinct blocks will be detectable on a properly black point calibrated display. Block 0 should be perfectly black, matching the borders of the display, and block 10 should be barely visible as distinct from block 0. If no difference can be distinguished between blocks 0 and 10, then the display is likely set too dark and will require an adjustment. For an adjustment to be accurate it must be performed under normal viewing lighting conditions; the black point for a brightly-lit room will be higher than for a dimly-lit room.

¹¹⁷ *Dynamic range* is the extent of values from lightest to darkest.

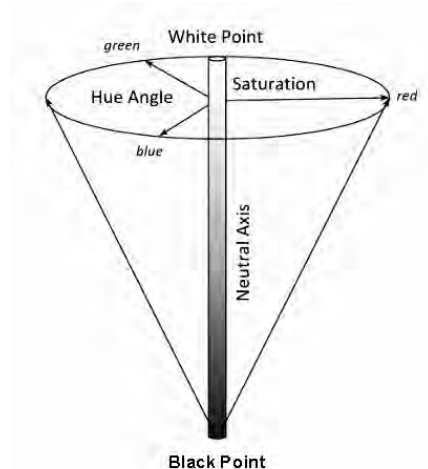


Figure 51. Relationship between neutral axis and white and black points in a RGB color space (adapted from Krig, 2016).

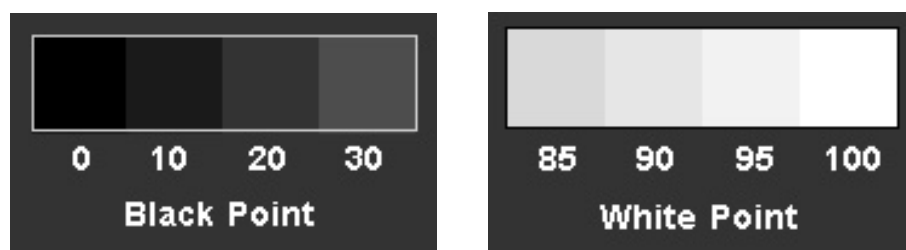


Figure 52. Calibration test patterns for viewing a display properly calibrated for black and white points.

A similar test pattern for calibrating the white point is shown in Figure 52 (right). Again, four distinct blocks should be detectable between blocks 85 and 100. Block 100 should be perfectly white, and block 95 should be barely distinguishable. If they appear to be the same, then the display's contrast is set too high, and highlights are blocked. Most displays work fine with contrast set at 100%. If this value is perceived as being too bright, or highlights are blocked, the contrast can be decreased, but a recalibration of the black point is required. In addition, the sRGB standard specifies a color temperature of 6500 °K. Most monitors provide the capability of setting color temperature, allowing the viewer to adjust this value for preferred whites.

Gamma correction.

Gamma can refer to a number of different concepts. In the context of producing imagery on a display, gamma refers to the nonlinear representation of a source image when it is reproduced on a display. In the simplest sense, digital displays reproduce an image in response to input voltages being applied to each pixel, for which there is a resultant luminance output (Burger & Burge, 2010). Gamma is the relationship between the numerical value of a pixel in a source image and the brightness (Luminance) of that pixel when viewed on the display (Perkins, 2012). The computer translates the numerical values in the image file into voltages sent to the monitor. In an ideal situation, the output luminance of a pixel on a display would be linearly related to the input voltage, as shown in Figure 53a. However, most displays are not linear,

which means that a change in input voltage does not produce an equal change in output luminance. CRTs do not behave linearly in their conversion of voltages into output luminance. And, while not inherent to their characteristics, LCDs usually also provide this nonlinear response. This nonlinearity can result in loss of detail in the shadows and blown-out highlights.

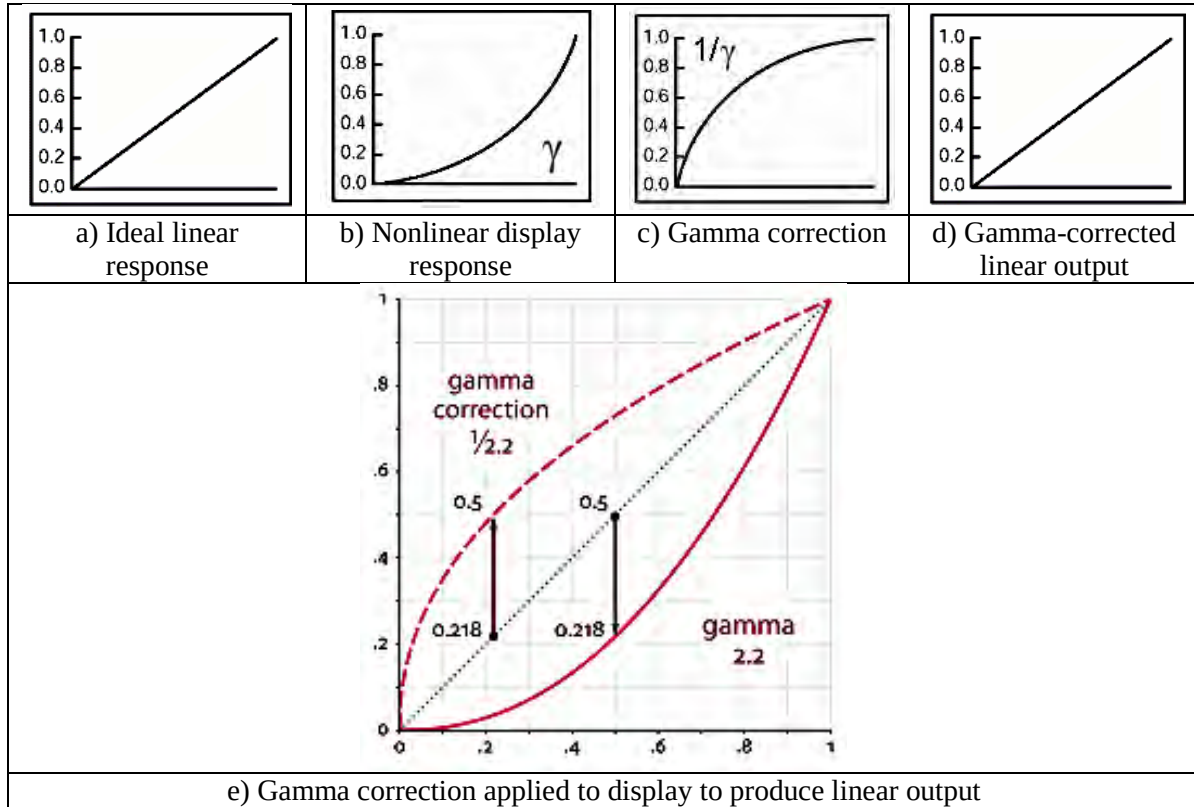


Figure 53. Gamma correction.

The typical nonlinear response of most displays is similar to that shown in Figure 53b. A display's actual response curve approximates a power-law function, as represented by the formula,

$$I_{\text{Output}} \propto V_{\text{Input}}^{\gamma}$$

where V is the input voltage, I is the output intensity (luminance), and the exponent (γ) is called gamma (Velho, Frery, & Gomes, 2009).

Gamma is different for every individual display device, but typically it is in the range of 2.0 to 2.4 (Bertoa, 2016). The native gamma of most CRTs is 2.5; LCDs have a gamma of 2.2. Having a gamma of 2.2 means that a pixel at 50% intensity emits less than a quarter (21.8%) of the light as a pixel at 100% intensity (Figure 53e). Adjusting for the effects of this nonlinear characteristic is called gamma correction. A combination of hardware and/or software performs this correction, shifting the gamma closer to 1.0, i.e., a linear relationship. This helps ensure that a change in pixel brightness in the source image translates into a proportional change in brightness on the display (Perkins, 2012). A gamma correction does not affect the black point

and the white point of an image, but either brightens or darkens the midtones according to the type of adjustment being performed.

In Figure 53c, the gamma correction for the nonlinear response (Figure 53b) is illustrated. For a gamma value γ , the gamma correction is $1/\gamma$. Figure 53d shows the gamma-corrected linear output.

Gamma correction changes not only the brightness, but also the ratios of red to green to blue colors. Colors viewed on a display with an "uncorrected" gamma will appear different from those viewed with a corrected gamma. When a computer and display exchange color information, ideally the relationship is one in which the eight-bit color input information per RGB color from the computer will be output accurately. However, the color of each pixel must be quantized to the number of bits available in the display's color space (Velho, Frery, & Gomes, 2009).

As an example, consider the RGB color vector defined as (0.5, 1.0, 0.5), which has sRGB values of 127, 255, 127. This color on a LCD monitor would be expected to appear as in the left box in Figure 54. However, recall that for a typical display gamma of 2.2, a 50% intensity produces only 21.8% of the light at 100%, then the 2.2 gamma applied by a display (if uncorrected) would produce the color with of sRGB vales 55, 255, 55, and would appear as the color of the right box in Figure 54 (Bertoa, 2016). The white point (255, 255, 255) is not affected (Figure 54, center).

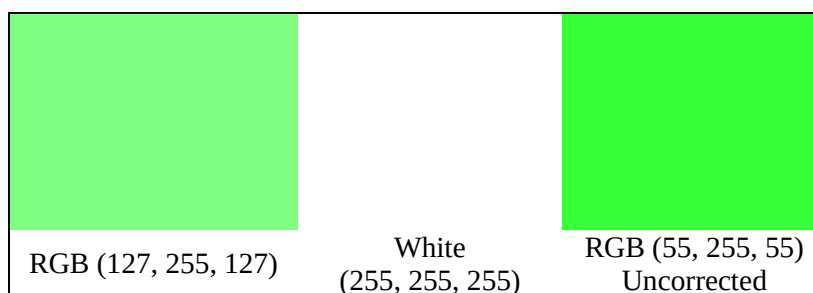


Figure 54. Example of uncorrected color gamma (right).

Displays are not the only devices that reproduce images. Printers are also display devices. When a printer has a default gamma of 1.8 (a typical value for commercial printers), then the printer output would match what is shown on the computer display only if the gamma of the display is also 1.8. Unfortunately, printer responses (gammas) vary widely across brands and models. In practice, a printer is more likely to be farther out of calibration than a display (Stucker, 2001). To ensure good color reproduction, both the display and printer must be calibrated, which includes matching gammas. As a rule, the display should be calibrated first and then the printer in order to obtain a good match between the display and printed images (Dillard, 2009).

In summary, different systems have different gamma values. This may produce nonlinearity in the transformation of luminance (brightness) and color information when images

are reproduced on a display device (e.g., display and printer). An effective gamma correction will deliver true colors and a good range of light, mid, and dark tones.

Color management.

The discussions of color spaces and the presentation of colors on chromaticity diagrams are not just theoretical in nature; they have practical applications. The process of maintaining color accuracy from start to finish, i.e., the progression of color information from capture/creation to reproduction, is known in the color industry as *color workflow*. Good color management is required to provide color consistency and predictability throughout the entire workflow; this is accomplished best through a clear understanding as to what happens to the color information in an image as this information progresses through one or more conversions from its original to its final color space. Color management considers the characteristics of input and output devices in determining the color data conversions for these devices (International Color Consortium [ICC], 2004). All devices vary via certain elementary parameters. These include the color and brightness of the primary; the color and brightness of the white and black points; and the tone reproduction characteristics of the primaries (Fraser, Murphy, & Bunting, 2004). In summary, color management is a term that describes the technology and techniques that translate the colors of an object (e.g., an image captured by a scanner or camera) from its original color space to the color space of an output device (e.g., displays and printers) (Stokes, Anderson, Chandrasekar, & Motta, 1996).

Beginning in 1993, the ICC began developing profiles to characterize device-dependent¹¹⁸ colors in a device independent way, thereby addressing problems in communicating color across open systems. Using these profiles, color management converts colors between a device's color space (e.g., RGB or sRGB) to and from a colorimetric color space (most often CIELAB),¹¹⁹ so as to perform color gamut mapping (Krig, 2016). Since each device can reproduce only colors within its own color gamut (range), gamut mapping is required to convert colors to the closest possible match.

Consider the simple (but common) workflow scenario depicted in Figure 55. A picture of an array of flowers is taken with a digital camera, transferred to a display for viewing or editing, and then sent to a printer. The camera produces an image of the flowers in an RGB color space (e.g., Adobe RGB).¹²⁰ The color management system will convert this to the sRGB color space for viewing on a display. A final conversion is made from the color space on the display to the color space of the print (i.e., CMYK). Printed images will never be an exact match to the images viewed on the display because of the conversion and remapping of color values that occur during the printing process. Optimally the printed image will closely match the original on screen, but it will never match it exactly because each has a different color gamut (Brooksmartstudio.com, 2010). To further illustrate this point, Figure 56 shows the difference between how colors might look on a computer display (RGB) compared to how they might be reproduced in print on an offset press or ink jet printer (CMYK).

¹¹⁸ RGB and CMYK color spaces are referred to as device-dependent or device-specific because the actual colors rendered from a given set of RGB or CMYK numbers depend on the device producing the color (Fraser, Murphy, & Bunting, 2004).

¹¹⁹ CIELAB is a key component of the color managed workflow.

¹²⁰ Most professional digital cameras allow selection of the output color space for JPEG and TIFF formats of sRGB and Adobe RGB.

Colorimetry.

Colorimetry is the application of metrology to color science. In the manner photometry deals with the measurement of light, colorimetry deals with the measurement, or quantification, of color. Its goal is to “describe” a color in such a manner as to “uniquely” and “unambiguously” distinguish it from all other colors (Wyszecki & Stiles, 1982; Johnston-Feller, 2001). Colorimetry describes colors in numbers (tristimulus values) and provides a physical color match using various instruments (e.g., colorimeters)¹²¹ (Yoshizawa, 2009). This numerical description is based on the concept all colors can be represented as combinations of the three primary colors associated with the human eye’s three cone receptors: red, green, and blue (see *Anatomy and Physiology of Color Vision* section). However, since color is a perception, it is not accessible to engineering measurement. As such, colorimetry is actually a metric of psychophysical color stimuli (Schanda, 2007).

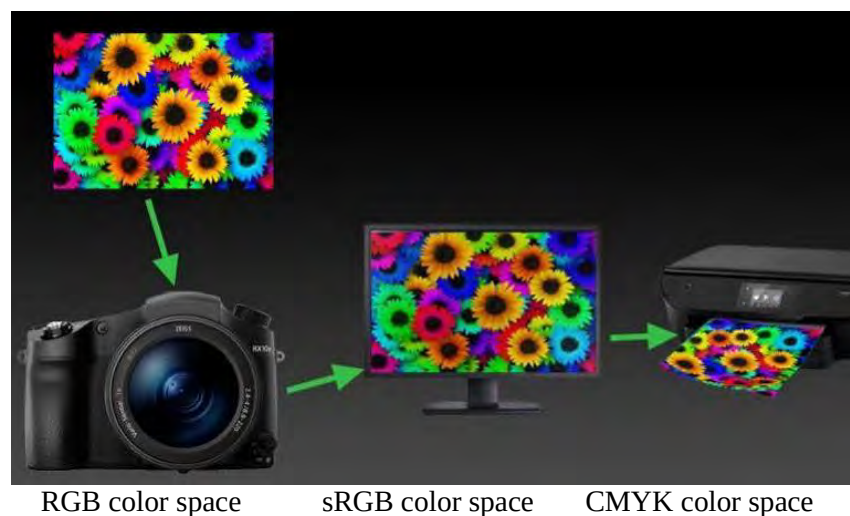


Figure 55. Example of a color management workflow.

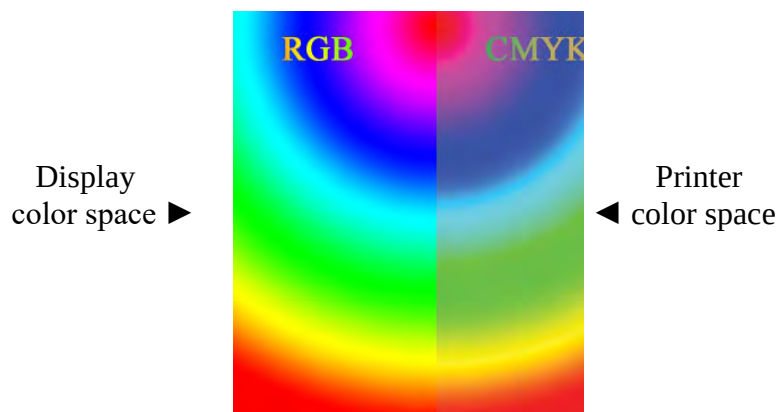


Figure 56. RGB and CMYK color space comparison.

¹²¹ Colorimeters, based on this theory of color perception, employ three photocells as receptors to see color in much the same way as the human eye. A number of tristimulus colorimeters are available today for color sampling, inspection, and quality control.

The goals of colorimetry are to incorporate properties of the human color vision system into the measurement and numerical specification of viewed surfaces or light sources and to reduce the variation that can arise in comparisons (Brainard & Stockman, 2010). This can include situations of image capture (e.g., cameras) and rendering (e.g., displays and printers) (Clymer & Rosa-Molinar, 2014); it is also extremely useful in determining color differences. Many of the major principles and methods relating to colorimetry have already been discussed. These include spectroradiometry, color temperature, color mixing, color models, tristimulus values, and chromaticity coordinates (see *Physics and Chemistry of Color* and *Color Science* sections).

The first colorimeters were developed primarily to measure the absorbance and transmittance of light through fluids. These colorimeters operated on the principle of the Beer-Lambert law – equal amounts of absorption occur in equal optical depths (thicknesses) in a substance, and, therefore, equal amounts of absorption occur in equal amounts of material.¹²² One of the earliest and most popular colorimeter (in the scientific world) was invented by Jules Duboscq, a French optical instrument maker, in 1854 (Stock, 1994). The Duboscq colorimeter was used in urine and blood analysis to determine concentrations of its components, to aid in medical diagnosis.

Another well-known colorimeter was developed by Joseph Lovibond, a London brewer in business in the 1870s. He was the inventor of the Lovibond Comparator (marketed in 1887 as the Tintometer) (Lovibond, 1895). His endeavor into colorimetry was driven by his attempt to use color matching as a means of grading beer (Johnston, 1998). The Tintometer utilized previously known color measurement principles – comparison of a sample to a calibrated reference. While finding great acceptance and use in many industrial communities (e.g., oil production, water quality measurement, and agriculture), the Tintometer faced considerable scientific scrutiny (Gibson & Harris, 1926). Much of the criticism, while probably motivated by scientific elitism, was focused on the lack of specification and control of grading filters used in the device. Lovibond continued to improve his device, addressing this criticism, eventually achieving compatibility with CIE standards; his company is still in operation today as The Tintometer Ltd.¹²³

Today, colorimeters can come in benchtop, handheld, and pocket models. They have a wide range of applications (e.g., paints, inks, plastics, textiles and apparel, food and beverages, pharmaceuticals, and cosmetics) and are commonplace in manufacturing where product quality can be monitored through color stability. Standard colorimeters do not operate too differently (in principle) from the colorimeters of Duboscq and Lovibond: a beam of light at a specific wavelength is passed through a sample solution via a series of lenses, which direct the colored light to the measuring device, where its color is analyzed and compared to an existing standard. Data are sent to a microprocessor that calculates the sample's absorbance (A) or transmittance (T) and presents results on a display. Modern colorimeters sometimes are classified as color densitometers, when density or concentration is being measured, or color photometers, when reflection or transmission is being measured (e.g., measuring the color spectrum of displays and colors produced by printers and copy machines).

¹²² The *Beer-Lambert law* (also known as Bouguet's law because of historical ambiguities) is a combination of associated laws developed by August Beer and Johann Lambert.

¹²³ The Tintometer Limited, Lovibond House, Sun Rise Way, Amesbury, Wiltshire, UK SP4 7GR.

Metamerism.

The tri-receptor designs of the human visual system (i.e., red, green, and blue cones) and in colorimeters (i.e., three photocells) lend themselves to an interesting color phenomenon known as metamerism. An observer looking at a colored object has no way of knowing from its appearance the spectral composition of the light stimulus (emitted, reflected, and/or transmitted). The perceived color of an object will depend on the eye's three cone responses to the SPD emanating from the object. The eye-brain visual system doesn't distinguish color by the individual wavelengths detected, only by their combined effect. Because of this, different spectral distributions will be perceived or (in the case of a colorimeter) measured as the same color. Spectra perceived as being the same color are called metamers. Metamerism occurs because each cone type responds to the cumulative energy from a broad range of wavelengths, meaning that different combinations of spectral energy can produce identical receptor response and color perception (or the same tristimulus values in a colorimeter) (Fulton, 2008). In Figure 57, two different spectral distributions are presented at the top of the figure. However, as shown at the bottom of the figure, both distributions have the same tristimulus responses (left) and result in the same color perception of brown (right) (Beall, Doppelt, & Hughes, 1995).

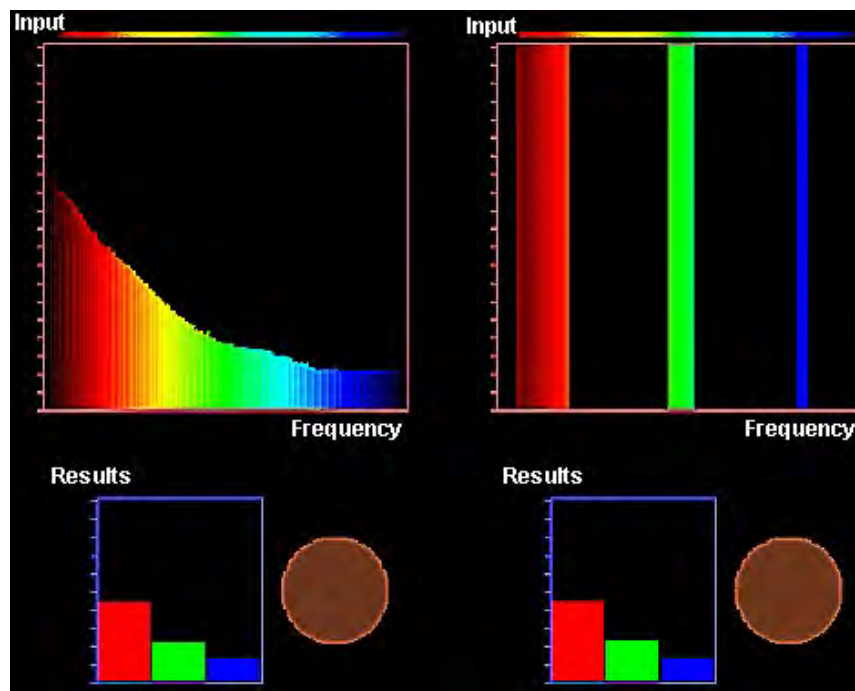


Figure 57. Example of metamerism (adapted from Beall, Doppelt, & Hughes, 1995).

One of the first technical recognitions of this perceptual phenomenon is accorded to the German physicist, mathematician, and polymath, Hermann Gunther Grassmann (Schubring, 1996). According to Grassmann's (1853-54) laws of color mixing, a color match is invariant under a variety of experimental conditions that may alter the appearance of the matching fields. Metameric matches also will hold even with the addition of a color surround or subsequent to (pre-) exposure to a reasonably bright color field (see *Color Perception* section) (Krantz, 1975; Smith & Pokorny, 2003).

Color questions.

Whenever and wherever visible light is present, there is the potential for color perception. In the environment, humans are inundated by color, both as presented by nature and as artificially created (manmade) (Figure 58).

Two fundamental questions are frequently encountered in even the most cursory discussion of color:

1. How many colors are there?
2. Are *black* and *white* colors?

The first question is ambiguous and would best be represented by three more precise questions:

- 1a. How many colors exist in nature?
- 1b. How many colors can be artificially produced?
- 1c. How many colors can humans perceive?



Colors in nature



Manmade colors

Figure 58. Colors in nature (left) and manmade colors (right).

For the question (1a) of how many “colors” exist in nature, the answer can be explored via two approaches. The first is via physics, which associates colors with the wavelengths in the visible part of the EM spectrum (typically between 380 and 750 nm). This is a continuous spectrum, having an infinite numbers of values. The second approach is to ask how many different SPDs of emitted, transmitted, and/or reflected light can exist. Again, the answer is an

infinite number; therefore an infinite number of potentially perceived colors can be presented by nature.

Humans have a long history of reproducing the colors present in nature, as well as creating new ones. These artificial methods include paints, dyes (including some inks), and electronic displays. Paints are liquid substances that are mostly applied to surfaces.¹²⁴ They achieve their color properties via pigments that use wavelength-selective absorption to modify reflected light. The major paint suppliers advertise upwards to 3,000 predefined color options (unfortunately with creative color names that are intended to inspire rather than define) (e.g., cotton candy pink, strawberry, wolf gray, and moonshine), making them available as color chip samples. In addition, using computerized color matching technologies, customized paints can be formulated to match virtually any color found in nature or manmade materials.

Similar to pigments, dyes achieve their color properties through selective absorption. But dyes differ from pigments in that a dye is a soluble colorant (pigments form suspensions). Dyes can be natural (e.g., produced from vegetable, animal, and mineral sources) or artificial (synthetic). The color achieved with a dye is the result of a myriad of factors besides the dye formula itself, which include solvent (usually water), temperature, humidity, dyeing time, and material being dyed (e.g., fabrics, foodstuffs, drugs, and inks) (Johansen, 2010; Waring & Hallas, 1990). As with paints, dye suppliers offer a large number of predefined formulations, but different dyes can be mixed in varying proportions, resulting in an infinite number of potential colors.

In CRT displays (e.g., televisions and older computer monitors), color is produced by mixing light from three different color phosphors. As discussed previously, the choice of these phosphors determines the color gamut (or range of colors) that can be presented. However, as an analog system, a color CRT can theoretically present an infinite number of colors to the eye.

Most displays used today for televisions and computer monitors are discrete (digital) devices. Therefore, the number of possible colors is finite, but still very large. As previously alluded to, in theory most computers can produce 16,777,216 different color combinations for display on a monitor (Fairchild, 2012). This number is derived from each of the red, green, and blue primary channels used to produce the image on the computer display being controlled by an 8-bit number. An 8-bit number can have 2^8 (or 256) possible levels (0 to 255). Zero is used to represent a color channel being fully turned off; the 255 value represents a color channel fully turned on.¹²⁵ Since there are 256 possible levels of red, green, and blue, there are $256 \times 256 \times 256$ (~16.777 million) different color combinations the computer can theoretically display. The display industry continues to increase the number of addressable pixels, and color depth¹²⁶ is experiencing an analogous increase from the common 8 bits to 12 bits per color (i.e., an increase from 24 bits to 36 bits for all colors combined). With 12-bit color (2^{12} or 4096 levels) this would allow a color capability increase to an incredible 68.7^+ billion colors ($4096 \times 4096 \times 4096 = 68,719,476,736$) (Larson, 2013). However, as is shown in the last of the three questions

¹²⁴ Plastics, resins, and rubber products are usually colored by pigments.

¹²⁵ Black is encoded as 0,0,0 for R,G,B, while white is encoded as 255,255,255.

¹²⁶ *Color depth*, also known as bit depth, measures the number of bits of information a pixel can store and therefore determines how many colors can be displayed. See *Digital color* section.

addressing how many colors exist, the number of *available* colors is not the same as the number of *useable* colors.

Question (1c) addresses how many colors humans can actually discern. Research has suggested that humans can discern between approximately 1000 levels of light-dark, 100 levels of red-green, and 100 levels of yellow-blue for a single set of viewing conditions.¹²⁷ This leads to a total of 10 million combinations or possible different colors (Wyszecki, 2006; Fairchild, 2011). Most other organisms “see”¹²⁸ a lesser number of colors, but these include colors that are not visible to the humans. Other than primates, most mammals have reduced color vision due to having fewer types of color receptors (typically two types: blue-reddish/green). Spiders, ants, flies, and honeybees can see colors in the UV that are invisible to humans, although they see less, if any, of the red end of the spectrum (Bertholf, 1931). For example, hawk moths, like humans, have three color receptor types (i.e., cones), but instead of the human red-green-blue, their receptors are UV-green-blue (Kelber, Balkenius, & Warrant, 2003). However, the spectral sensitivity range of reptile vision does not include UV energy but instead extends into the IR (Goris, 2011). Birds, arguably, have the widest color vision, possessing four to five cone types, providing sensitivity from the UV, through the visible spectrum, into the IR (Sherwood, Klandorf, & Yancey, 2012).

However, an investigation of how many colors the human visual system can perceive is not as analytical as the previous approaches to the question. Color perception varies greatly from person to person, affected by a host of factors, e.g., age, gender, experience, memory, and cultural background (Clark, 1985; Carroll, 1994). The human visual experience is a complex one, involving not just the obvious factors of brightness and color, but also other sensory information, such as smell and sound, all interacting in an associative manner via the cognitive function of memory. Color vision itself is gene-linked, and mutations in these genes result in color deficiencies that affect a person’s ability to perceive certain colors (Foley & Matlin, 2010) (see *Anatomy and Physiology of Color Vision* section).

Numerous methods have been used to investigate individual differences in color perception. These methods include tasks of color matching, detection of spectral lights, and discrimination between lights on the basis of differences in color spectra (Smith & Pokorny, 2003). However, while successful in expanding the understanding of human color vision, these methods have been equally successful in confirming the wide variability in human color perception, e.g., studies show that humans with normal color vision often make different color matches (Webster & MacLeod, 1988).

Research seems to indicate the human brain copes with the near infinite number of colors by grouping them into categories of hues and shades (Eckstut & Eckstut, 2013). In general, humans attempt to differentiate between colors by assigning color names. However, Berlin & Kay (1969) found that virtually all languages only have a small number of basic color terms, and these colors generally cluster about the same dominant wavelengths. Malkoc, Kay, & Webster (2005) confirmed these focal choices but found considerable individual differences in stimuli selected for matching with unique color terms.

¹²⁷ This calculation is based on one of the three proposed theories of color vision, Hering’s opponent process theory.

¹²⁸ Any discussion of color vision in non-human organisms must be caveated with the theory that color is a perception. Other organisms do detect ranges of spectral energy, but this does not imply the type of association that humans equate with the concept of color.

In summary of the first color question of how many colors “exist,” the number of potential colors existing both in nature and as the result of manmade activities is essentially infinite. In contrast to this, the human visual system appears to be ideally limited to approximately 10 million colors. However, this may be misleading, as human color perception varies greatly from person to person, being affected by a number of factors, e.g., fatigue, environmental lighting, background, age, and color deficiencies (Foley & Matlin, 2010) (see *Color Perception* section).

The second most encountered question (2) in color discussions addresses the issue of whether black and white are considered to be actual colors, in the sense that red, green, etc., are. The concepts of black and white are ancient in origin and appear to be elemental in nature, considered to be associated with night and day, respectively. Almost every language and culture has words for these two concepts (Geiger, 1872; Kouwer, 1949). However, as might be expected based on previous discussions, the answer is not a straight forward one and depends on the perspective or context. The two major perspectives are that of the physical sciences, which requires colors to be associated with specific wavelengths, and that of the psychological and cognitive sciences, which interpret colors as perceptions, complex and not fully understood processes originating in the cones of the retina and ending in the multiple visual cortices in the brain.

A good place to begin answering this question is the investigation of the definitions of the two terms, black and white. Most physics textbooks define, or at least describe, *black* as the absence of light (i.e., energy at “none” of the wavelengths in the visible spectrum) and *white* as the presence of energy at “all” visible wavelengths (Figure 59) (Brancazio, 1975; Beiser, 1992; Serway & Faughn, 1999).¹²⁹ Usually the first in-depth encounter with the concept of black in physics is in the discussion of the interaction between light (EM radiation) and matter, where a “theoretical” perfect absorber, a body that absorbs 100% of the radiation of all wavelengths incident upon it and does not reflect or transmit any radiation, is defined as a *blackbody*.¹³⁰ Perhaps the most intriguing physics associated with the concept of black is that of stellar *black holes*. When a star, an immensely massive object, at the end of its lifecycle collapses rapidly under its own gravitation, its entire mass can be contained in a sphere of just a few miles in diameter. With such a large mass density, the surrounding space-time geometry is so curved light travels in a circular or elliptical path and is prevented from escaping; hence, the star does not allow emitted light and may be considered “invisible,” prompting the name “black hole” (Brancazio, 1975; Space Telescope Science Institute, 2015).

In the discussion of the visible spectrum, a particular color was associated with a particular wavelength (or range of wavelengths) of EM energy; this is often referred to as a spectral color.¹³¹ Therefore, it seems reasonable, using this definition, to conclude black cannot be deemed a color, i.e., if there is no energy at any wavelength, there can be no color.

¹²⁹ The online Merriam-Webster Dictionary (2015) defines black as “characterized by the absence of light and white as “consisting of a wide range of frequencies.”

¹³⁰ Paradoxically, a blackbody is also a perfect *emitter* of radiation. The spectral distribution of the energy radiated by a blackbody is continuous and depends only on its temperature.

¹³¹ Most of the colors perceived are not spectral colors, but instead are combinations of wavelengths. For example, the color perceived when viewing the IHADSS P-43 phosphor-based display as green contains energy at most or all of the visible wavelengths but with the peak energy at a wavelength of 543 nm, which falls within the band of wavelengths associated with the green part of the visible spectrum (Figure 15, right, p. 32).

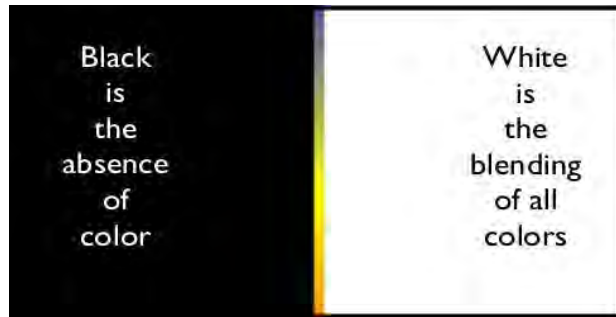


Figure 59. Physics definition of black and white (Source: Matt Cauthron, Digital Arts Technology Academy, Palm Springs, CA).

Although grounded in physics, the above associations with the concept of black all derive their names from what is perceptually experienced by the human visual system when no visible light energy falls on the retina (i.e., no photons are absorbed by the rod and cone photoreceptors). “Black” is what humans associate with darkness...the absence of light.

In physics, the concept of white (light) typically is first introduced in the study of optics via the discussion of Isaac Newton’s famous experiment of using a prism to separate white light into the colors of the visible spectrum (Figure 3, p. 14). White is defined as the sum of all possible colors (wavelengths) and, therefore, cannot be a color because it is not associated with a specific wavelength. In essence, and quite confusingly, white is colorless i.e., without color, because it consists of all colors.

Contrariwise, white is the “color” assigned to a number of common, naturally occurring phenomena; it is the color of sunlight (as per Newton), snow, milk, chalk,¹³² and a number of minerals,¹³³ e.g., calcite, dolomite, kaolinite, and muscovite. The label “white” is used to describe the visual perception experienced when all three types of retinal cone photoreceptors are stimulated equally (see *Anatomy and Physiology of Color Vision* section).

With respect to color science, white, along with black, are known as achromatic¹³⁴ colors. The term achromatic is frequently used as a synonym for black, white, and all grays; these are referred to as pure achromatics. A common definition of this term is “without color or hue,” but in general usage the term may refer to any “color” lacking the color attribute of hue. Achromatic colors have zero saturation and vary only in brightness (lightness or value). Deane Judd described black and white as the two extremes of achromatic (surface) colors (Judd, 1941). If brightness is 0, then the surface will have the appearance of black; if brightness is 1, the surface will have the appearance of white.

In summary, black and white are unique both within the context of physics and of visual perception. Black and white were possibly the first color pigments used in cave paintings and have a strong presence in religious, social, cultural, and mythical symbolisms (Heller, 2009). As far back as prehistory, black and white have been associated with numerous examples of dualism

¹³² Natural chalk (not that associated with classroom blackboards) is a type of limestone, consisting of the mineral calcite.

¹³³ Virtually all minerals can exhibit a wide range of colors depending on the presence of impurities.

¹³⁴ Sometimes, the label *neutral* is used interchangeably for *achromatic*.

expressed in such opposing principles or concepts as light and darkness, day and night, all or nothing, and good and evil. In modern times, common examples of this dualism include such examples as “white hat” vs. “black hat,” “black and white thinking,” and the wearing of white at weddings and black at funerals. When a situation involves a simple choice between things that are clearly opposite, especially between good and bad or right and wrong, it is frequently described as a “black and white” decision.

In cultural terms of black as a color choice, some European and oriental cultures associated black with refinement and distinction. Black clothing was a preference of the wealthy and nobility during the European Renaissance period, and this fashion choice eventually expanded to all levels of society (Gage, 1999). In western cultures, black normally symbolizes death or mourning; whereas in the Chinese culture, it is white (De Bortoli & Maroto, 2001).

As an amusing historical note demonstrating the layperson’s acceptance of black as a color, after the American inventor Henry Ford introduced the Model T Ford automobile, a common joke was “You can have any color you want, as long as it is black.”¹³⁵

Color as a Method of Information Coding and Presentation: A Timeline

Information is data or knowledge that has meaning to the user (observer). This knowledge is stored via a selected method of encoding, presumably known to and understood by the intended user. Visual information is encoded using symbols, which are defined as images, alphanumerics¹³⁶ (singularly or in combinations), or shapes, which themselves can employ encoding characteristics, e.g., size, texture, position, orientation, and color (Figure 60). Over millennia color has served as an important, powerful, and increasingly prevalent means of (information) communication (Yu, 2014). To fully appreciate the complexity and expansion of the use of color, not just in the limited (but expanding) applications in Army aviation, but in virtually all facets of modern society, it is worthwhile to briefly follow the ascent of color through the various historical communication formats and technologies.

Exactly when color was first used as a technique for encoding information is difficult to determine. Color most likely was first used by early man for its inherent visual appeal in body decoration and cave art (Morris-Kay, 2010). Then, at least as early as the Neolithic period, color began to take on symbolism (e.g., *red* was associated with power and later with love and fidelity; *purple* was associated with royalty) (Birren, 1988). Neolithic hunter peoples considered red to be the most important color, endowing it with life-giving powers, and burying red ochre into graves of their deceased (Douma, 2008). Eventually, color was used to convey specific information (e.g., *red* for stop and danger; *yellow* for caution). However, it is unlikely there were clear demarcations for these transitions; and, as the number of uses of color increased, usage within each purpose expanded. An approximate timeline tracing some of the major developments, or milestones, in the evolution of color production, presentation, and usage, from prehistoric to modern times, is presented in Figure 61. While focusing on color as a means to encode and

¹³⁵ Actually, when Ford introduced the Model-T, black was not one of the four available colors (gray, green, blue, red). It was not until 1914 that black became the only color choice (McCalley, 1994). However, in 1909, Ford did express an intention to implement a “black only” color scheme (Ford & Crowther, 1922).

¹³⁶ Alphabetic and numeric characters.

convey information, the technologies of producing (and reproducing) color, necessarily, will be major parts of the discussions.

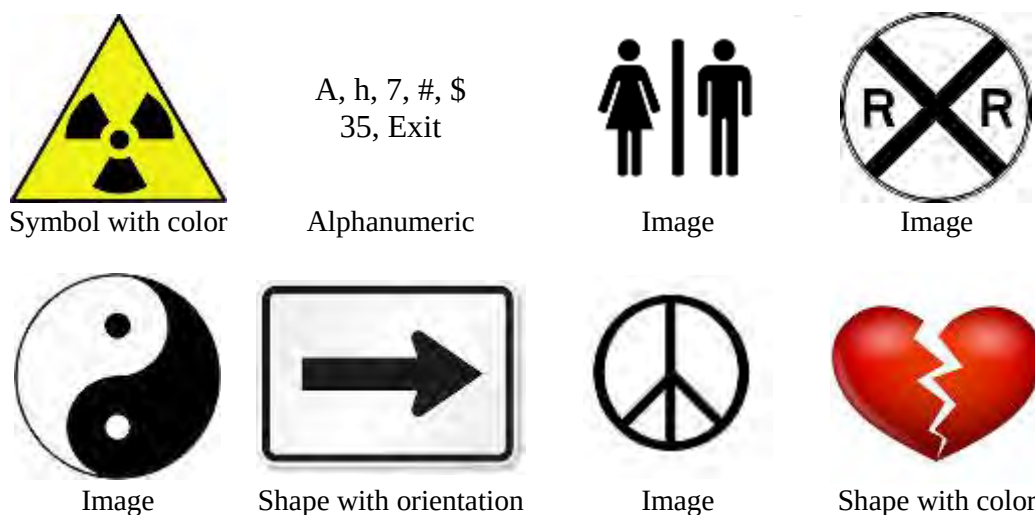


Figure 60. Examples of information encoding using various methods.

Archaeologists have uncovered evidence dating back at least 350,000 years in caves in Zambia of the use of color for esthetic purposes, being employed first in body decoration. Other cave findings in Africa, as well as in India and China, have shown the widespread use of color in art and decoration by early man (Jones & MacGregor, 2001; Marean et al., 2007; Balter, 2011).

Pigments and dyes.

The first known color-providing substances (colorants) were pigments, which were made from naturally occurring materials (e.g., insects, plants, iron and manganese oxides, charcoal, and mammal bone-marrow fat) (Orna, 2013). Pigments consist of extremely fine particles of these materials suspended in a liquid (binder) that form a paint film that bonds to the surface to which it is applied.

In 2011, the discovery in Blombos cave, South Africa, of grinding tools and pigment fragments that were dated to 100,000 years ago was cited as being the earliest known “workshop” for the organized production of pigments (Henshilwood et al., 2011). Used initially for body decoration, pigments became the basis for the “paints” that were used to produce the first art in prehistoric times, cave paintings. In cave paintings, the pigments stuck to the wall partly because they became trapped in the porous cave wall, and partly because the binding media (the spit or fat) dried and adhered the pigment to the wall surface. The color palette of prehistoric artists was restricted to the pigment materials that were available in the local area, the most common being carbon black and red ochre¹³⁷ (Feller, 1987). There is evidence the Egyptians used the mineral cuprorivaite to create the “first” blue – Egyptian blue – 4,500 years

¹³⁷ Ochre is a natural earth pigment containing iron oxide; colors can range from yellow to brown; red ochre obtains its reddish color from the presence of a large amount of the iron oxide hematite.

ago (c2500 BCE), which is considered to be the first synthetic pigment (Orna, 2013; Royal Society of Chemistry, 2016). Mercury sulfide (HgS) was one of the most important red colors

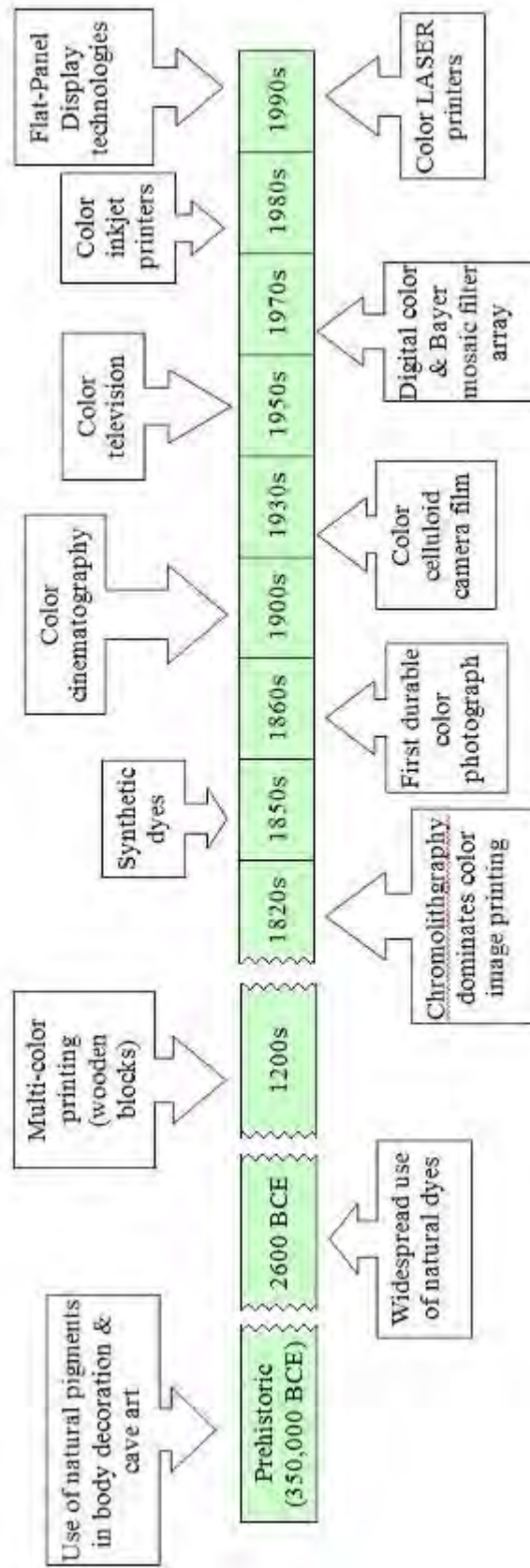


Figure 61. Timeline for some of the major milestones in the ascent of color usage.

in ancient times and was known as vermilion or cinnabar; a common bright yellow coloring material, found on prehistoric cave walls in Egypt dating to 4000 BCE, was orpiment (As_2S_3) (Orna, 2013).

The next big revolution in color was the colorant group known as dyes. The major difference between dyes and pigments is their solubility (i.e., the tendency to dissolve in a liquid). In dyes the coloring matter is dissolved in a liquid (vs. suspended in a liquid for pigments) and absorbed into the material to which they are applied. Originally, dyes were made with natural substances mixed with water and oil and used to decorate skin, jewelry, and clothing. The majority of natural dyes were from plant sources – roots, berries, bark, leaves, wood, fungi, and lichens. Other natural sources included insects and sea life. A common red color used in ancient dyes was madder, derived from plants of the Rubiaceae family; the most important yellow dye was weld, which was derived from various parts of the plant *Reseda luteola* (or Dyer's rocket) (Orna, 2013).

The earliest widespread use of dyes is attributed to China and India circa 2600 BCE (Donatelli, 2015), becoming well-established by 1050 BCE (Wu & Tian, 1986). The use of dyes for clothing and decorative fabrics quickly became widespread, with the dyeing of wool for clothing becoming an established craft in Rome by 715 BCE (Druding, 1982). However, while the first recorded mention of fabric dyeing dates back to almost 5,000 years, recent but yet to be confirmed, archaeological findings from explorations of caves in the foothills of the Caucasus Mountains hint at the discovery of dyed flax fibers dating back 36,000 years, predating the Chinese and Indian history of the use of dyes (Balter, 2009).

A major drawback to natural dyes was their limited color range. Being of natural materials, availability also was frequently an issue. As expected, the law of supply and demand spurred efforts to develop artificial (or synthetic) dyes. The first non-natural dye can be traced to the 1770s, but commercialization of synthetic dyes did not develop until the 1850s (Waring & Hallas, 1990). As often occurs in science, chance played a role in the discovery of synthetic dyes. In 1856, the chemist William Henry Perkin was experimenting with synthesizing the anti-malarial drug quinine. In an experiment with a compound called aniline, a component of coal tar, he obtained a black precipitate. On testing its solubility, he accidentally discovered that alcohol extracted a purple color. This substance was discovered to readily dye silk and to be much more stable to sunlight exposure than any other previously available natural purple dye (Open University, 2007).

Color filters.

Another milestone in the human experience with color was attempts to create color by modifying available light sources. For millennia, the most common light sources were oil/fat lamps (c10,000 BCE), candles (c2000 BCE), gas lamps (c1800), and incandescent lightbulbs (c1880). These light sources are considered broadband and perceived as white light sources. To achieve color using such full-spectrum sources, the concept of filtering can be employed. In the simplest theory, the white light is viewed (or passed) through a transparent material that allows some wavelengths (colors) to pass through but blocks others.

The manufacture and use of color filters has a long history and employed many different materials: liquids, dyes, fabrics, glass, and plastics. As examples, in the theater, dating back to Shakespeare, glasses of wine or colored water, silk fabric, and gelatin were used as filters to change the color of stage lighting (Trumbell, 2008); the use of stained (colored) glass¹³⁸ in churches, mosques and other important buildings has inspired patrons for over a thousand years (Campbell, 2006). One of the earliest descriptions of deliberately adding a colorant to a material (e.g., glass) to change its color properties is in *De Coloribus et Artibus Romanorum* (Colors and Roman Art) by the monk Eraclius (Heraclius) in the 8th and 9th centuries (Bjork, 2010). Today, filters are widely used in decorative and theatrical lighting, scientific applications, photography, advertising, and many other applications. Perhaps the best known filters are the Eastman Kodak Wratten filters¹³⁹ (Figure 62, left). Designed originally for use in photography, these filters are used in a number of scientific and industrial applications (e.g., forensic science and observational astronomy).



Figure 62. Examples of Kodak Wratten photographic (left) and generic absorptive color (right) filters.

Optical filters may be one of two types: absorptive and interference. The simpler type of filter is the absorptive filter, constructed of either glass or plastic (e.g., acrylic and polycarbonate). This filter type works on the principle of selective color. The filter substrate has dissolved in it organic or inorganic compounds (e.g., pigments and dyes). Such filters can absorb a wide range of wavelengths, and the color of the filter is the color of the transmitted light (Williamson & Cummins, 1983). Examples of absorptive filters are shown in Figure 62 (right). The principle of a simple “red” absorbance filter is presented in Figure 63.

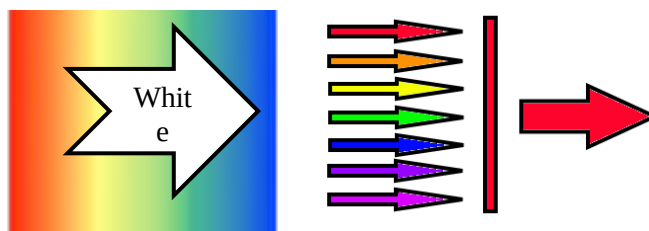


Figure 63. Basic principle of an absorptive filter modifying a white light source to allow transmittance of red light only.

¹³⁸ Stained glass refers to both colored and painted glass.

¹³⁹ Wratten filters are named for their inventor, Frederick Wratten.

Another type of color filter is the interference filter, also known as dichroic or “reflective” filters, so named because they reflect unwanted wavelengths of the light and transmit the remainder. This filter type is based on the principle of interference, and such filters are constructed by depositing thin layers of optical coatings on a glass substrate. These filters have four basic design types: short wavelength pass, long wavelength pass, bandpass, and notch filters.¹⁴⁰ While more efficient and precise in their control of which wavelengths are transmitted, interference filters are more costly and generally used in applications where their extra cost is warranted, e.g., microscopy, laser communication, and spectral radiometry. Figure 64 shows an example of an interference filter, reflecting blue and red light (i.e., magenta) and passing green.

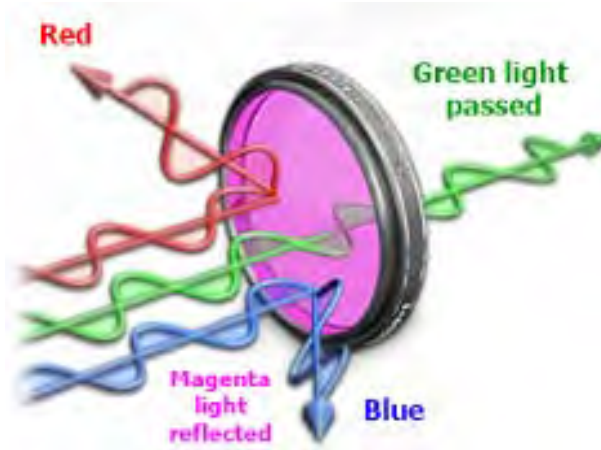


Figure 64. An example of an interference filter that reflects blue and red (i.e., magenta) light and passes green light (Source: Florida State University).

A classic and historically interesting application of color filters is the use of colored lights as railway signals, which dates back to the 1920s. Railway signals are a means of communication, usually between personnel on the train and other personnel on the ground or another location on the train. Ground-based signals also are used to direct railway traffic. These signals have been both optical (visual) and acoustic (auditory) in design. In early railway history, vanes, semaphores, and lamp lights were the first optical signaling devices, with only the latter being effective at night, in tunnels, and over long distances (Solomon, 2003). Until electricity became widely available in the 1920s, the lights were oil or gas lamps. After the installation of electricity, lamps were useable in many daytime lighting environments. The directional motions and temporal exposure periods of the hand and lamp signals provided the communication codes (Calvert, 2004).

Color was an integral element of all except the very earliest optical signals. It was an informational element of flags (red, green, and white), semaphores (white, red, and blue), vanes (white, red, blue, and green), and lamps (white, red, green and yellow).¹⁴¹ The filters employed were composed of glass (lenses). In all cases of color signals, detection and color discrimination were dependent on physical factors as luminance, distance, and size; atmospheric conditions; and

¹⁴⁰ A *bandpass* filter passes frequencies within a certain range and rejects (attenuates) frequencies outside that range. A *notch* filter rejects a narrow bandwidth of wavelengths while passing all others.

¹⁴¹ A number of additional colors (e.g., orange and purple) were investigated, with some incorporated over time.

visual performance of the viewer, which includes visual perception issues and illusions (see *Color Perception* section).

Color printing.

It can be argued the invention of printing was the first technological revolution in communication of information. The first step in this revolution was woodblock printing during the T'ang Dynasty in China c618 CE and culminating in 868 CE with the printing of the *Diamond Sutra*, the oldest dated full-length book, containing both text and illustrations (Gosling, 2011; Visually, 2012). Printing in more than one color was first achieved by using multiple (and different) engraved blocks (one for each desired color) impressed into fabric or paper. This method, laborious and time demanding, was in widespread use in Asia and Europe as early as the 13th century. The first book printed in more than one color is cited as the *Latin Psalters*, a collection of Psalms published by Fust and Schoeffer in 1457. Its pages contained elaborate decorative initials, printed in red and blue ink. Between about 1580 to 1644, during the latter part of the Ming dynasty in China, techniques were perfected for mass production of multicolored book illustrations (Beretta, 2010). While multiple color woodblock prints persisted through the next few centuries, full-color illustrations were almost predominately hand colored.

For centuries, printing provided the dominate mode for the dissemination of information, and this was greatly enhanced by numerous inventions of moveable types (e.g., wood, ceramic, and metal) in Asia and Europe. In this pre-industrial period, printed (or written) information traveled faster and wider than the spoken word. Most of this information was in the form of text. However, as early as the 1600s, in Britain, newspapers would incorporate one or two elaborate initials or a single front page wood cut graphic. Printers and publishers became increasingly aware of the tremendous impact the presence of illustrations would have on circulation. Hence, newspapers began to send artists to sketch people and events (especially battles); these pen and ink drawings would be converted into engravings, first as wood block engravings and later as metal plate engravings. Once these “pictures of time” were available, the printing process made their distribution rapid and widespread. In Britain, the January 19, 1806, issue of the *Times* contained its first illustration, an engraving of naval hero Horatio Nelson’s funeral. In 1842, *The Illustrated London News* became the world’s first fully illustrated weekly newspaper. The first issue contained 32 wood engravings; the Christmas 1855 issue contained the first color pictures ever printed in an English newspaper (British Library, 2016). The first American illustrated newspaper was *Gleason’s Pictorial Drawing-Room Companion*, founded in 1851. In America, it was not until 1891 that color would first appear in the nation’s daily newspapers when *The Milwaukee Journal* printed a blue-and-red bar on its front page to commemorate the inauguration of a new Governor, George W. Peck (Glaberson, 1993).

Jacob Le Blon, a German painter and engraver, is credited with developing the first three- and four-color printing processes (Lilien, 1985; Lowengard, 2006), which was similar to the CMYK color system discussed in the *Color spaces and models* section. His work served as the foundation of many modern color printing methods. However, it was the 19th century that proved to be the turning point for technical developments in color illustrations used in books and magazines (University of Delaware Library, 1996). By the 1820s, a number of methods of color printing were being explored, with the color lithograph (chromolithography) process eventually

becoming the most successful and commercially viable printing technique. Invented in 1798 by Aloys Senefelder, basic lithography was a chemical-based printing technique based on the property of mutual repulsion of oil and water. The desired image was drawn on the surface of a flat (lime)stone or (zinc) metal plate with a hydrophobic medium such as a wax crayon. The plate was moistened, and an oil-based ink was applied to the plate, which immediately bonded with the wax crayon lines. The inked plate and a sheet of paper were pressed together, transferring ink to paper. For a simple monochrome pen and ink drawing, this would be the only press run required. However, as early as 1818, Senefelder had suggested that multiple color prints could be produced employing several different runs with up to four different color inks – black, red, yellow, and blue. The same sheet of paper would be placed precisely over the re-inked plates, eventually creating a satisfactory color lithograph copy (Ferry, 2003).

As the 19th century progressed, chromolithography was perfected and became the least expensive and most widely used printing method for achieving complex colored images, having a profound effect on print advertising. Chromolithography remained dominant until the 1960s (Meggs & Purvis, 2011). But advances in the field of photography, which would become the preferred method for rendering text and graphics, challenged this supremacy. The first challenger was the halftone photomechanical process developed in the 1880-90s, which used a screen to transform photographic images into an array of dots, and then in the 1960s by offset photolithography (a type of photolithographic printing). However, since technology is ever advancing, these color printing techniques soon were replaced by the arrival of the digital revolution with its inkjet (1980s) and laser (1990s) color print-on-demand technologies (New York Public Library, 1999; Polsson, 2015).

Inkjet printing technology first appeared in the late 1970s. The first color inkjet printers appeared about 1985. A number of different inkjet technologies have been developed. Most consumer inkjet printers operate by a method known as drop-on-demand that sprays ink droplets onto paper via thousands of tiny chambers or reservoirs in the print head, the part of the printer that transfers the ink to the paper. Monochrome (B/W) text and images are printed using black ink provided in one cartridge; color text and images use a second cartridge (or three separate cartridges) containing cyan, magenta, and yellow inks. In the print industry, cyan, magenta, yellow, and black are used as the primary colors (see *Color Science* section). This combination is known as the CMYK color system, where “K” represents “black.” Some high end inkjet printers optimized for photo printing have an expanded six-color system known as CcMmYK (Steinmueller & Gulbins, 2006). It extends the standard four-color CMYK system by adding light cyan (lower case c) and light magenta (lower case m).

Laser printing technology was developed at the Xerox Corporation’s research facility in Webster, NY, in the late 1960s. International Business Machines Corporation (IBM) is credited with the first laser printer, the IBM 3800, in 1979; the first desktop color laser printer, the Quality Microsystems (QSM) ColorScript Laser 1000, was released in 1993 (O’Malley, 1993). Laser printers, as the name implies, use a laser beam to produce an image on a drum. This action creates a charge distribution on the drum, which then is rolled through a cartridge of toner, a powder mixture of carbon and other substances. The toner is attracted to the charged areas on the drum and then transferred to paper via heat and pressure. Monochrome (B/W) printing uses a

single toner cartridge; color printing requires additional cyan, magenta, and yellow cartridges. Hence, color laser printers also use the CMYK color system.

Both inkjet and laser color printers are capable of reproducing an acceptable range of colors, referred to as the color gamut (see *Color Science* section), for most users. However, the CMYK color system does present problems with presenting low saturated, low intensity colors. Also, some deep red, deep green and deep blue colors cannot be represented in the CMYK gamut; adding additional colors, such as with the CcMmYK system, can assist in alleviating this deficiency. The available color gamut of a specific printer is determined by the type, number, and color of the colorants (inks and toners), as well as the paper type.

Color photography and cinematography.

Into the mid-1800s, wood and metal engravings were the major techniques of producing illustrations, whether in black and white or in color. These techniques were plagued with inherent problems of the laborious effort and time delay involved in bringing illustrations to press. The photographic process was a solution to these problems. However, as with the printing process, considerable effort and experimentation had to be exerted before photography (and eventually color photography) would be the leading technique for capturing and reproducing images. Photography is as much a complex and revolutionary mode of information communication as printing was. Photography provides the ability to faithfully capture images of events as they occur and people as they are at that instant in time, along with providing a comparatively rapid method to reproduce these images.

It would be the public's enthusiasm for images of war that provided photography the opportunity to quickly rise in use and popularity in spite of it being a relatively new invention not well understood by the general public. In Europe, it would be the Crimean War (1853-1856), and in America, the Civil War (1861-1865) where photography would rise in prominence and take hold as the leading method of documenting important news of the day. Photographers like Roger Fenton, James Robertson, Carol Szathmari, Mathew Brady, and Alexander Gardner ventured out to battlefields with their bulky and heavy camera equipment carted about in wagons to capture the realism of the war (Cosgrove, 2014).

While giving due recognition to the invention of the Camera Obscura (Latin for *dark room*) in the 13th century, practical photography as we think of it today was introduced in 1839 in the form of the daguerreotype (Newhall, 1982; Rosen & Devries, 2002). It is difficult to determine the first who, when, and where of a given technology, and this is certainly true of color photography. The early 1800s saw a number of creative, scientifically sound, but impractical, attempts to produce color photographs. One famous example was the first full-color photograph by Edmond Becquerel in 1848. Unfortunately, today his photographs are considered only as laboratory curiosities since an exposure of up to several days was required and the colors were so light-sensitive they faded right before the viewer's eyes (Becquerel, 1848).

In 1861, physicist James Clerk Maxwell used an additive color approach (see *Color Science* section) he conceived in the 1850s (Maxwell, 1855), producing a positive color image using three glass plate negatives exposed through red-, green-, and blue-colored water filters.

From these negatives, positives were made and projected on top of each other, through the same color filtration, to produce an image. This was a complex procedure and viewing the image was problematic. However, this set of three separations is frequently cited as the first durable color photograph (Uhrhane, 2005). In 1868, Louis Ducos du Hauron patented multiple ideas for color photography based on the three-color, subtractive color principle for producing color prints on paper (see *Color Science* section). Although not technologically practical at the time, they anticipated some of the later successful color processes (Solbert, Beaumont, & Card, 1952). In the 1880-90s, Frederic Eugene Ives developed and demonstrated a three-color separation process following Maxwell's methodology. Ives took three separate black-and-white photographs of the subject through carefully registered red, green, and blue filters. Transparent positives of the three images (Kromograms) were viewed in a Kromoscope (or chromoscope), which used red, green, and blue filters and transparent reflectors to visually combine them into one full-color image. Prepared sets of images, called Kromograms, were sold for viewing in this device. Although producing high quality color, Ives' device was not a commercial success (Sipley, 1851). Incremental advances throughout the rest of the 1800s and into the early 1900s ultimately led to the 1907 introduction of the autochrome glass plate (Lavedrine & Gandolfo, 2009). Developed by the Lumiere brothers in France, the Autochrome Lumiere (as it was formally known) used an additive color process and was considered to be first commercially successful color photography product until the mid-1930s' arrival of the color celluloid film era represented by such iconic brands as Kodachrome,¹⁴² Fujifilm,¹⁴³ Kodacolor,¹⁴⁴ Agfacolor,¹⁴⁵ and Polaroid¹⁴⁶ (Mees, 1929; Weil, 1933; Lavedrine & Gandolfo, 2013). Figure 65 depicts examples of color photography techniques: Maxwell's three-color plates (left), the Autochrome Lumiere (middle), and Eastman Kodak Company's Kodacolor film.

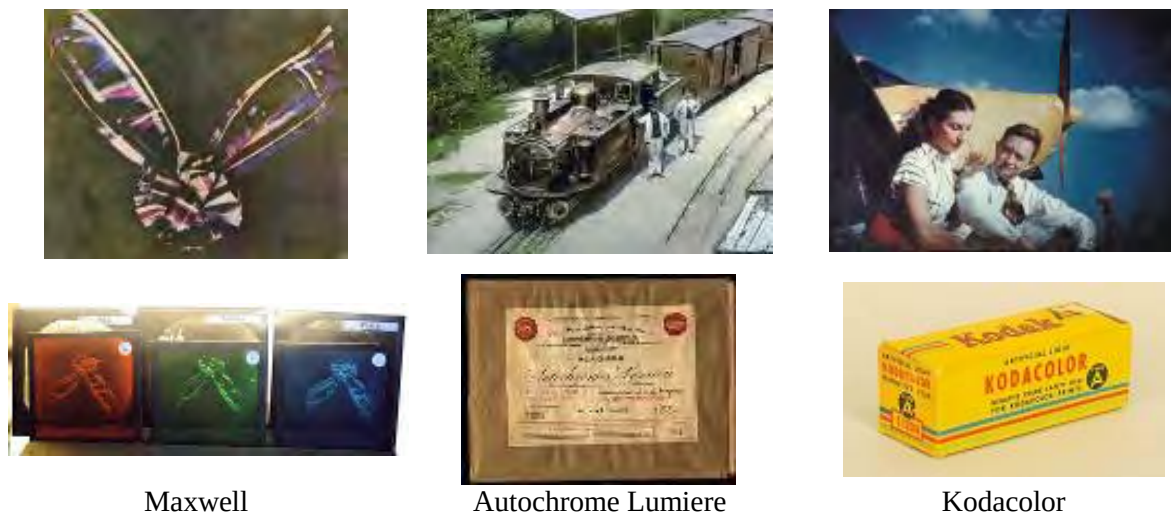


Figure 65. Maxwell photography of a Tartan ribbon, c1869 (left); Autochrome Lumiere, c1918 (middle); and Kodacolor, c1949 (right).

¹⁴² Kodachrome is a brand name for a non-substantive, color reversal film introduced by Eastman Kodak Company, Rochester, NY, in 1935.

¹⁴³ Fujifilm is a brand name for Fuji Photo Film Company Ltd, the first Japanese manufacturer of photographic films (established in 1934).

¹⁴⁴ Kodacolor is a brand name for a film for prints introduced by Eastman Kodak Company, Rochester, NY, in 1942.

¹⁴⁵ Agfacolor is a brand name of a series of color film products made by Agfa of Germany. The first Agfacolor film was introduced in 1932.

¹⁴⁶ The Polaroid Corporation, Minnetonka, MN, introduced Polacolor, the first instant color film, in 1963, for use in the Model 100 Land camera.

Similarly, as with color printing, the mid-1990s brought a technological revolution in color photography. At the center of this revolution was the digital camera. Steve Sasson, an engineer at Eastman Kodak Company, is credited with the invention of the digital camera in 1975. However, Eugene F. Lally of the Jet Propulsion Laboratory, Pasadena, CA, first described how to create digital photographs using an array of photosensors in 1961 (Belbachir, 2009). At the simplest level, digital cameras capture color similar to the way color film captures color – by breaking down and recording the light as three primary colors – red, green, and blue.

Initially, these cameras used a specially designed prism beam splitter with filters (Figure 66) to split the incoming light into its RGB components that fell onto three different light-detecting sensors (e.g., charge-coupled devices [CCDs]) (Figure 67, left) (Hess, 2016). The major breakthrough was the development of the color filter array (c1975), a mosaic of tiny color filters placed over a single image sensor to capture color information. The most common type of color filter array is called the "Bayer" array and consists of alternating rows of red-green and green-blue filters (Figure 67, right). Because the human eye is more sensitive to green light than both red and blue light, this array has twice as much area dedicated to green than to red or blue. The result is an image that appears less noisy and has finer detail than could be accomplished if each color had equal area (Cambridge in Colour, 2016b).

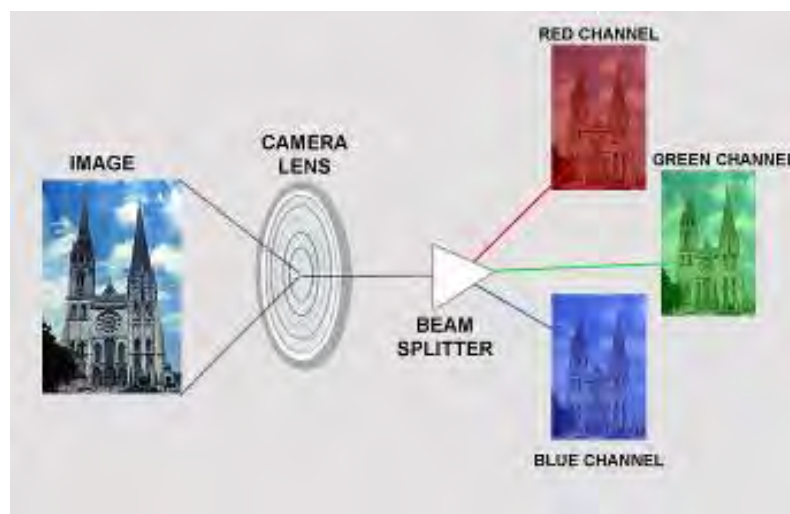


Figure 66. Use of beam splitter to split incoming light into its RGB components.

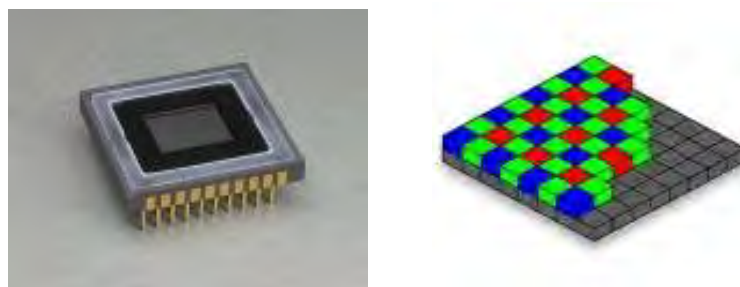


Figure 67. Example of a CCD image sensor (left) and illustration of a Bayer color filter array (right).

A final topic under color photography to be considered here is motion picture technology or cinematography. By definition, a motion picture is a continuous set of still images (frames) captured and presented at a rate high enough to produce the perception of continuous motion. The current American industry standard is 24 frames per second.

The earliest widespread methods of producing color motion pictures were known as autonomous or applied coloring methods. These originally B/W films, as early as 1895, were colorized through a number of techniques involving tinting, toning, hand coloring, and stencil coloring (Flueckiger, 2013; Hess, 2016). In tinting each B/W film had to be cut into individual frames, submerged in dye baths, and then reassembled (Eastman Kodak Company, 1916). While less labor intensive, toning required a more complex procedure, a chemical reaction that replaced the silver image in the emulsion of the positive film with color metal compounds, e.g., iron ferrocyanide (blue), copper ferrocyanide (red-brown), and silver sulfide (sepia). Hand coloring was performed on each individual frame using acid dyes applied with very fine brushes (Brock, 1931). Stencil coloring (known as Pathechrome or Pathecolor) was introduced in 1904 and remained in use until 1928 (Kelley, 1931). This technique required the manual cutting, frame by frame, of the area which was to be tinted onto another identical print, one for each color. Three to six colors were used. Figure 68 depicts examples of three of these early motion picture coloring methods: tinting (left), toning (middle), and hand coloring (right).



Figure 68. Examples of adding color to motion picture film via tinting (left), toning (middle), and hand coloring (right).

Beginning in the same period as the applied coloring (c1897), a number of methods based on additive three-color mixing using filters were attempted. (Wall, 1925). In 1897, Hermann Isensee patented a method using a rotary shutter with three 120° filter sectors (red, green, and blue). This shutter had to be employed during both filming and projection. A number of similar methods based on a rotary filter continued over the next decade. In 1906, George Albert Smith created the first commercially successful color motion picture process. It was an additive two-color method called Kinemacolor (Brown, 2012). It both filmed and projected a B/W film using alternating (rotary) red and green filters.

The first useful subtractive color motion picture methods were introduced c1920. Although still employing B/W film and color filters, projection did not require special equipment. These methods were mostly two-color processes and resulted in a limited color range (gamut), i.e., no blues. The next major breakthrough in color cinematography was the

Technicolor¹⁴⁷ process. Although invented in 1916, this three-color subtractive color method was introduced only in 1922 and did not reach full development until 1932, by which time it was renowned for its ability to provide a wide range of vivid, highly saturated colors. Its final stage of development was known as “Three-strip” Technicolor, getting its name from using three separate B/W rolls of film exposed through a complex combination of beam splitters and color filters within a single camera (Hoch, 1942). The three negatives were printed onto a special film substrate. This process would be further reduced to a single roll of film (the monopack) in 1941 (Friedman, 1945; Hess, 2016). As with other subtractive color methods, no special projection equipment was needed.

Technicolor would reign until a less expensive color film process, Eastmancolor,¹⁴⁸ became available. This type of film was a refinement on the German color process known as Agfacolor, first developed in 1932, tested during the 1936 Summer Olympics in Berlin, but not available worldwide until the end of WWII. Eastmancolor was released in 1950. It required no special lighting or laboratory processing. Its color delivery was less vivid than what was provided by the Technicolor process, but color in motion pictures was no longer a novelty, and low cost and ease of use made Eastmancolor the dominant color cinematography method until the arrival of digital color cinematography.

In 1985, a major project was undertaken by the entertainment broadcasting community to “colorize” vast libraries of earlier B/W films. Using digital manipulation, each film was scanned and colored frame by frame in a modern electronic version of the hand coloring method introduced in the late 1890s (Hess, 2016). In 2000, as the power of computer processing increased, a technique known as *digital intermediate* was introduced, allowing an entire film (B/W or color) to be scanned, digitized, and manipulated pixel by pixel.

Today, the film projector is rapidly being replaced by its digital counterpart. The chemistry of film (and color) and mechanical projectors have been replaced by a series of digital images stored on hard drives and a digital projector. About the only holdover in technology is the projector lamp bulb that produces the light to form the images. There are two major digital projector technologies: LCD and the Digital Light Processing (DLP) technology, with DLP currently being the most prevalent.

DLP projectors are based on Digital Micromirror Devices (DMDs) (Texas Instruments, 2014) (Figure 69). DMDs are silicon semiconductor chips. The surface of these devices is covered by as many as a million microscopic mirrors, each one representing a pixel in the projected image. In this system, a high-power lamp shines light through a prism beam splitter that separates (via filters) the light into the component colors red, green, and blue. Each color beam hits a different DMD. Each DMD reflects the monochromatic image back to the prism, which recombines the colors. The red, green, and blue components mix to form a full-color image, which is projected on the screen (Harris, 2002).

LCD projectors operate by reflecting high-intensity light off of a stationary mirror covered with a LCD. Based on the digital signal, the projector directs some of the liquid crystals

¹⁴⁷ *Technicolor* is the trademark for a series of color motion picture processes pioneered by Technicolor Motion Picture Corporation (a subsidiary of Technicolor, Inc.), now a division of Technicolor SA, Issy-les-Moulineaux, France.

¹⁴⁸ *Eastman* color is a trade name of Eastman Kodak Company, Rochester, NY.

to transmit the reflected light and others to block it. In this way, the LCD modifies the high-intensity light beam to create an image (Harris, 2002).

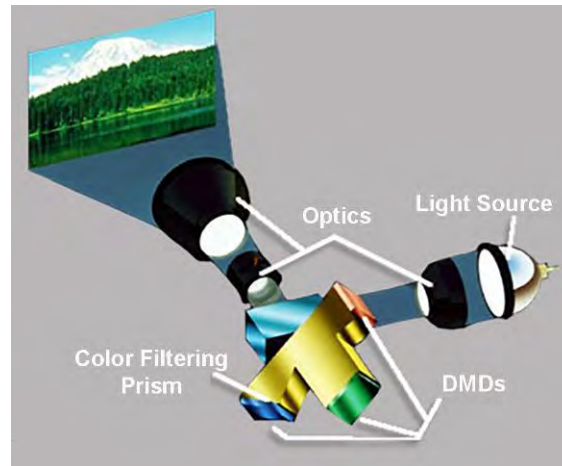


Figure 69. Basic components of DLP digital projector (Image credit: Texas Instruments).

While display technologies always are leapfrogging each other, LCD technology is generally considered to provide the most accurate colors. LCD colors appear more natural. DLP projectors are perceived as producing more saturated colors and deeper blacks (Projector People, 2016).

Color displays.

A number of display technologies have been developed for presenting color images for viewing. The first of these was the analog CRT. The first prototype was built in 1897; its use in television broadcasting was demonstrated in 1925; and CRTs became the dominant display for the next 70 years, and today almost half of all homes in the US still have at least one CRT device (Harold, 1976; Alcon & Linnel, 2014). While primarily associated with television (Figure 70, top, left), CRTs have been used for decades in scientific instruments (e.g., oscilloscopes) and computer monitors.

The basic operating principle is light is emitted when an electron beam strikes a phosphor coating on the inside front facing surface of a vacuum tube (see *Achieving color in displays* section). Color CRT displays (using three electron beams exciting a pattern of three color phosphors dots) entered the scene in the 1950s.¹⁴⁹ It became the dominant television in 1966 (Butler, 2006). The choice of the three color phosphors determines the range of colors (color gamut) that can be presented. As an analog system, a color CRT can theoretically present an infinite, but bounded, number of colors.

Since the 1990's a number of other display technologies have achieved prominence in the display market. These technologies include liquid crystal, plasma, electroluminescence, and OLED. Displays based on these technologies are collectively known as flat-panel displays,

¹⁴⁹ The National Broadcasting Company (NBC) broadcasted the first coast-to-coast color program, the Rose Bowl Parade, in 1954.

which takes its name from the contrast between the flat screens of displays using these technologies and the curved surfaces of CRT tubes. But, there the similarity ends; the light-producing mechanisms of these new technologies are very different (see *Sources and origin mechanisms of color* section).



CRT color television (Source: Zenith)



LCD computer monitor



Plasma color television



OLED phone display (Source: Samsung)

Figure 70. Examples of color display technologies.

The physics and chemistry behind these is not as recent as their late arrival to the display market implies, e.g., liquid crystals were discovered in 1888; electroluminescence was discovered in 1907 (Hart, Lenway, & Murtha, 1999); and the first LCD and plasma displays were demonstrated in the mid-1960s (Castellano, 2006). However, several factors slowed the rise of these technologies. First, while CRT displays were bulky, heavy, and had large power consumption, they produced high quality imagery, a good color gamut, and long lifetime. CRT displays were a high standard for insurgent display technologies to have to meet or surpass (Mentley, 2002). Second, there was a lack of manufacturing capability for these new arrivals. Newer machinery and innovative techniques had to be designed and developed to work with the novel display materials (e.g., liquid crystals). Third, these newer technologies initially presented with lower performance when required to operate in wide temperature ranges and to provide sufficient sunlight readability. Nonetheless, these problems were overcome, and today these new displays have surpassed CRT displays in their presence in the home, in business, in industry, and in the cockpit.

All flat-panel displays initially were monochrome, i.e., all text and graphics were presented in one color. In CRTs, this one color was typically white, hence the use of the term “B/W” to describe the output of early televisions. However, in CRTs the single color is determined by the choice of the phosphor coating on the inside of the vacuum tube (see

Achieving color in displays section). In addition to white, other monochrome colors used in CRTs include yellow, red, and green. Full-color CRTs first arrived in the 1950s, but took a decade to become the most common display in the home or in the workplace. Color was achieved by using three electron beams striking triads of red, blue, and green phosphor dots or strips (Figure 14, middle, p. 31). A B/W CRT display and examples of other monochrome displays are presented in Figure 71.



Figure 71. Examples of monochrome (single color) displays.

In LCDs, the individual liquid crystal cells act as small shutters, opening and closing to allow or prevent light from a backlight to be viewed. The liquid crystal cell itself has no color. In monochrome LCDs, the choice of backlight determines the color of the output. Initially, inexpensive florescent lamps were used as backlights, resulting in a B/W output. While inexpensive, this type of lighting was inefficient and posed a safety hazard, as they contained mercury. LED backlighting has become the backlighting of choice in most current LCDs (Morrison, 2013). A color LCD uses three subpixels with red, green, and blue color filters to create each color pixel (Figure 14, right, p. 31). The use of these filters means LCDs produce colors by subtracting colors from white light. This approach makes it difficult for these displays to maintain color accuracy and vividness (Diffen.com, 2016).

In plasma displays each pixel is a small cell of plasma or charged gas, somewhat like a tiny neon light (Figure 72); hence, these displays also are known as gas discharge displays. IBM Corporation built a monochrome plasma display in the 1980s that presented orange letters against a black screen. Today's color plasma displays consist of a grid of cells in which gas reacts with phosphors in varying degrees in red, green, or blue subpixels. Colors are more accurately reproduced with plasma technology than with any other display technology, including LCD. Black levels in plasma displays also are slightly better than in LCDs.

OLEDs are the most recent emerging display technology. As their name implies, they are LEDs that use an organic compound film as its source of light emission (see *LED and laser sources* section). OLEDs are monolithic devices, consisting of a series of organic layers between two electrodes (Figure 11, p. 25). As these displays are self-emissive, they do not require backlights, reducing thickness and power consumption. Each subpixel can be switched off completely, producing an absolute black. This ability gives OLEDs deep black levels and consequently remarkable contrast. One method of achieving color in OLEDs is to use an

architecture that stacks the red, green, and blue subpixels on top of each other, which offers a wide color gamut and greater color depth (Tsujimura, 2012).

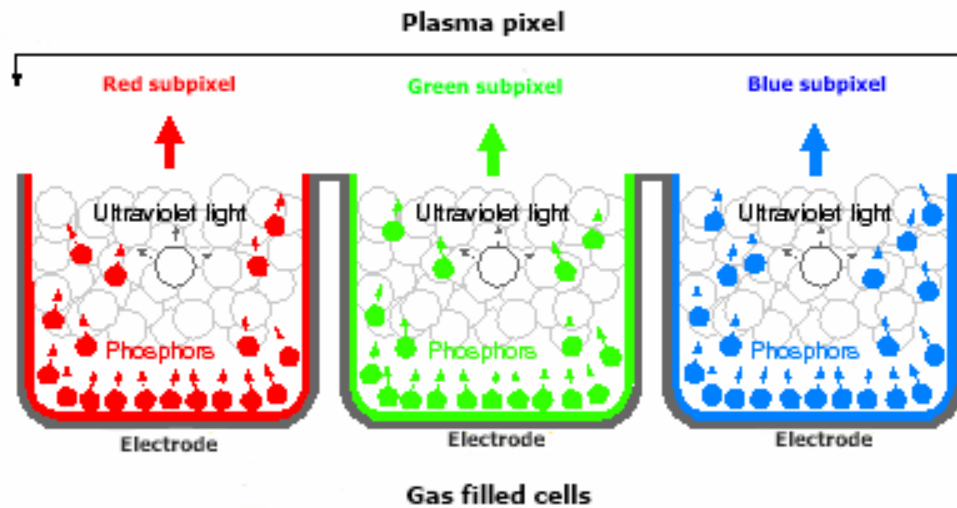


Figure 72. A plasma display color pixel, consisting of three subpixels (red, green, and blue).

Digital color.

From the use of natural pigments for cave painting to the use of celluloid films in photography, images were analog only. Today, the digital image reigns. A digital image is defined as an electronic version of an analog real-world scene or document (Cornell University Library, 2003). The conversion process is known as digitizing, and involves sampling and quantization. The original scene is sampled and converted into an array of dots or pixels. Each pixel is assigned a tonal value (black, white, or shade of gray or color) (Figure 73), which is represented in binary code as a string of binary digits (bits), i.e., zeros and ones. (*Note: A group of eight bits is commonly called a byte.*) The binary codes for each pixel are stored in a sequence by a computer, after which the bits can be interpreted and read by the computer to reproduce the original scene on a display or in print.

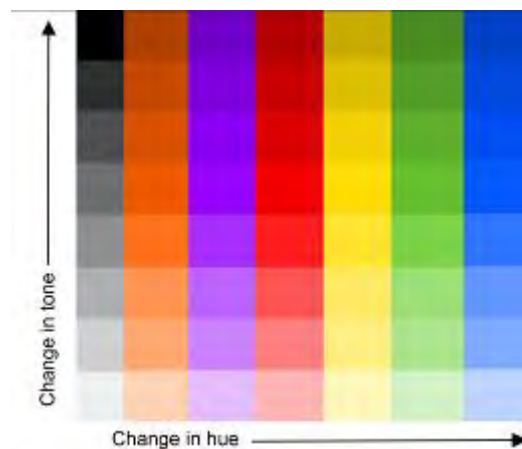


Figure 73. Depiction of multiple levels (tones) for grayscale and color images.

The number of bits used to define each pixel is known as *bit depth*. Digital images can be produced in B/W (bi-tonal), grayscale,¹⁵⁰ or color (*color depth* is used with color). Since bit depth quantifies how many unique tone levels (shades) are available, images with higher bit depths can encode more shades (or colors). A B/W image is represented by pixels consisting of one bit each, which can represent two levels (tones) (black and white), using the values 0 for black and 1 for white (or vice versa) (Figure 74). A grayscale image is composed of pixels represented by multiple bits, typically two to eight. The number of shades of gray available using n bits is 2^n , therefore, a B/W image ($n = 1$) only has two (2^1) levels, black and white. A grayscale image expressed in two bits has four (2^2) levels or shades; and 256 (2^8) levels for eight bits. To be able to represent the eight levels of grayscale in the left-most strip in Figure 73, three bits of encoding would be required (i.e., $2^3 = 8$).

The color (bit) depth in a color image quantifies how many unique colors are available in an image's color palette. Color depths typically range from 8 to 24 bits per pixel. In a 9-bit RGB color palette, which uses 3 bits for each color component, $(2^3)^3$ or 512 different colors are available. With a 24-bit color (referred to as *True Color*)¹⁵¹ image, the bits are grouped into three 8-bit bytes: eight bits for red, eight for green, and eight for blue. Combinations of those bits are used to represent $(2^8)^3$ or slightly more than 16.7 million colors. Figure 75 provides examples of various bit depth (and color depth) images (see *Achieving color in displays* and *Color questions* sections).

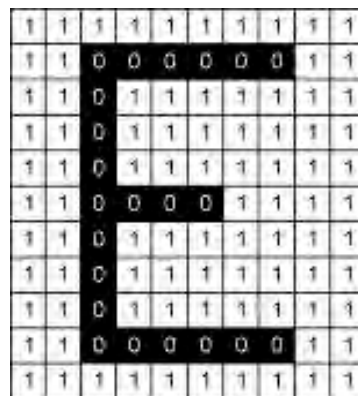


Figure 74. A simple bi-tonal digital image of the letter “E.”

Virtually all modern entertainment, industrial and military displays are digital with color as a now expected and sometimes even required capability. Digital imagery offer the advantages of easy storage and recall, search capability, editing and restoration capability, and real-time processing, which can include noise filtering, feature detection and enhancement, and analysis. In aviation, digital image presentation, predominantly via full-color AMLCDs, has become commonplace in cockpit Primary Flight Displays (PFDs), which present attitude, airspeed, altitude, heading, navigation, and other critical flight data.

¹⁵⁰ A *grayscale* is a series of neutral colors, ranging from black to white, or vice versa.

¹⁵¹ Usually, *true color* is defined to mean 256 shades of red, green, and blue, for a total of 256^3 or 16,777,216 color variations

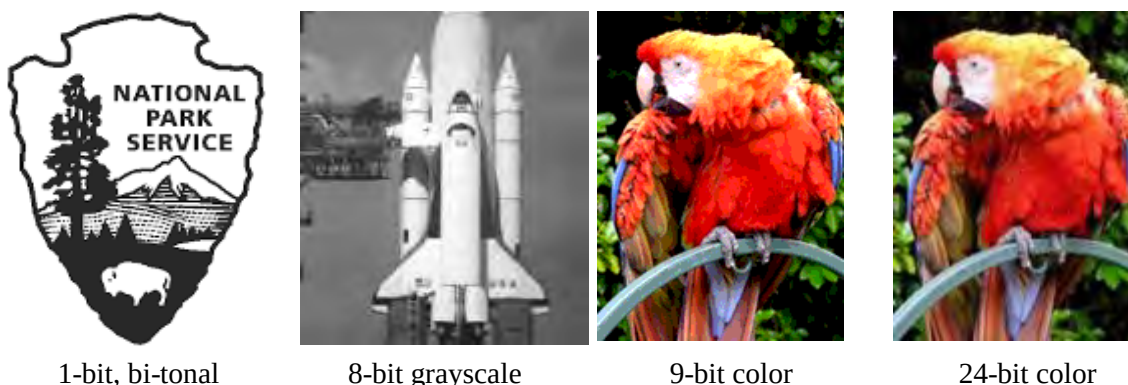


Figure 75. Bit depth: 1-bit bi-tonal, 8-bit grayscale, 9-bit color, and 24-bit color images. (Photo credit: Ricardo Niemietz)

The future of color.

It is appropriate to close this section with a look at what the future of color may bring. Even after millennia of usage, new ways to both produce and use color continue to be developed. As continuing advances in color science are made, it is only reasonable that new technologies will arise, bringing new uses and wider color gamuts.

Solid-state lighting is one of today's leading growth areas of technologies. Driven by the need for improved efficiency in lighting and the phasing out of the incandescent lightbulb, solid-state lighting research is on the rise. Solid-state lighting generates light using semiconducting materials rather than via burning, incandescence, or gas-discharge mechanisms. To increase user acceptability in the home, commercial, and public domains, this new lighting must provide not just greater efficiency, but must do so with the low cost, high brightness, and both the broad-spectrum and color range currently available with incandescent lighting. LEDs, especially OLEDs, are the leading solid-state candidates (Cangeloso, 2012; Khanna, 2014). Also, substantial effort is being put into the development of phosphor materials that offer the possibility to tune emission color over a wide range and maintain color stability (among other properties) (Birkel, Denault, George, & Seshadri, 2012). OLEDs are already showing their potential in the television, computer display and automotive industries and will eventually be a viable choice for aviation displays (Berlitz & Krstajic, 2015; Held, 2016). A unique capability of OLEDs (especially AMOLEDs) is their ability to be manufactured on plastic substrates, forming flexible displays, which allows for a wide range of mounting schemes (Figures 76 and 11, right, p. 25) (Koden, 2016). An OLED display is self-emissive, not requiring a backlight (similar to CRTs but unlike current AMLCDs). They are characterized by a number of properties that make them excellent candidates for aviation displays: low power consumption, wide operating temperature range, video response rates, full-color capability, and wide viewing angle ($>160^\circ$, due to being a Lambertian¹⁵² light source). Current OLEDs have demonstrated lifetimes of typically 10,000 hours (Rash, Harris, & McGilberry, 2005). They also have delivered the durability and environmental robustness demanded by aviation and other occupational applications (Hack, Weaver, Mahon, & Brown, 2001; Hack et al., 2003). Lighting specialists

¹⁵² A *Lambertian* surface reflects or emits equal (isotropic) luminance in every direction.

believe OLEDs may make panoramic cockpit displays possible in the near future (Pope, 2002). OLED microdisplays are a prospect for virtual reality military displays (Peters, 2006).



Figure 76. Flexible display capability of AMOLED technology (Source: Samsung).

In solid-state LED lighting, the achievement of white has been a major goal. Meeting this goal must include achieving high CRI values, i.e., good color rendition. The typical white LED uses the principle of additive mixing to generate white light. In the most common approach, the multi-chip method, the brightness values of the individual R-G-B color LED chips are regulated so as to produce white light. While more costly than individual LEDs, there are more serious disadvantages: a low CRI (20-60%) and a low luminous efficacy at the white point (Osram Opto Semiconductors, 2010).

New approaches are being investigated to manufacture “white” LEDs that provide excellent CRI and maintain high efficiencies. One approach already primed to accomplish this is the hybrid LED, a mixing of special white LEDs that have been shifted into the green range (known as EQ-white) and combining amber or red LEDs into a single-chip design. The resulting LEDs have shown CRI values as high as 98% (with a CCT of 3000 °K), as well as providing very good luminous efficacy and lifetime values.

One of the most promising new color technologies is that of quantum dots, a nanotechnology (Figure 77).¹⁵³ Quantum dots are tiny particles, or nanocrystals, of a semiconducting material with diameters in the range of 2-10 nm (the diameter of 10-50 atoms).

Like LCD materials, the science of quantum dots has taken over a quarter of a century to meet its expectations. They were first discovered in 1980 (Ekimov & Onushchenko, 1981). Quantum dots display unique electronic properties, intermediate between those of bulk semiconductors and discrete molecules, partly the result of the unusually high surface-to-volume ratios for these particles (Kastner, 1993). The most apparent result of this characteristic is fluorescence, wherein the nanocrystals can produce individual colors determined by the size of the particles (Figure 77) (McDowell, Wright, & Hammer, 2010). The ability to tune optical and electronic properties by changing the crystallite size has become a trademark of quantum dots (Sigma-Aldrich Co., 2016). Their size gives them a unique ability to convert light into nearly any color in the visible spectrum with very high efficiency. Energy output can range from the IR to the UV. In the visible spectrum, larger dots emit longer wavelengths (e.g., reds), while smaller dots emit shorter wavelengths (e.g., blues) (Chen, Hardev, & Yurek, 2013).

¹⁵³ *Nanotechnology* deals with dimensions and tolerances of less than 100 nm, especially the manipulation of individual atoms and molecules.

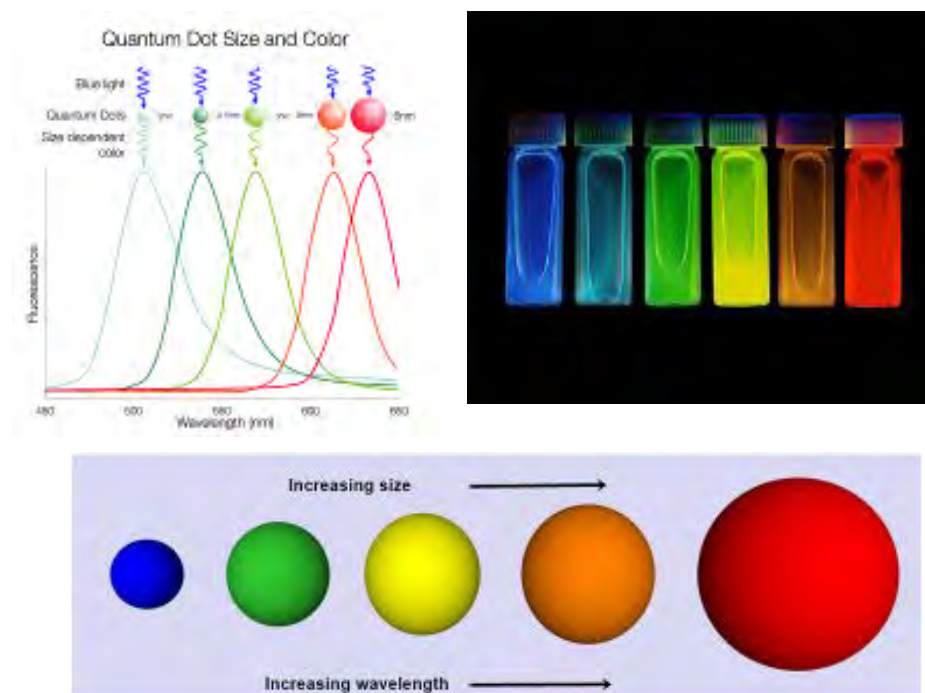


Figure 77. Quantum dot nanotechnology.

Quantum dot displays (being marketed as QLEDs) have a wide range of applications from smartphones to tablets to televisions (Turton, 1995). Being inorganic, quantum dot technology is more durable than OLEDs because they are more resistant to oxidation than are organic substances. Quantum dots are enabling next generation video features like High Dynamic Range (HDR)¹⁵⁴ and Wide Color Gamut.¹⁵⁵ However, QLEDs may not deliver an image quality superior to OLEDs. One reason for this is OLEDs completely shut off individual pixels, providing a “true” black and hence extremely high contrast ratios. In addition, QLEDs may have difficulty handling motion blur at higher refresh rates. However, HD televisions using early-generation QLED technology are already available, and other display technologies have clearly shown time tends to overcome early difficulties. QLEDs may become the next color display technology of choice sooner than projected.

But new technologies are not needed to expand color availability; new tricks with old technologies also are advancing color science. The color gamut of printer inks is being expanded through the optimization of spectral reflectance properties (Chen, Berns, & Taplin, 2004); new pigmented and dye-based inks are being investigated (Wilhelm, 2000); and a new spectrum of high-performance color pigments, paints, and coatings are under development (Little, 2016).

One new and novel use of color in medicine is a technology developed by researchers at Rochester Institute of Technology (RIT), Rochester, NY, that unobtrusively monitors cardiac activity of patients in an emergency setting. Their status is monitored using videos cameras and software that would immediately alert staff if the patient’s condition deteriorates. The technology

¹⁵⁴ *High Dynamic Range* (HDR) refers to the difference between the very brightest (whites) and darkest (blacks) images a television can produce. Televisions with HDR provide more dramatic, high contrast images.

¹⁵⁵ *Wide Color Gamut* refers to the ability of a television (or other displays) to present more saturated, vibrant colors by using quantum dots.

works using light reflecting off the skin that undergoes subtle changes in color as the heart delivers blood to and from the face (Couderc et al., 2015). Tracking color variations over time provides a signal analogous to one obtained using a photoplethysmography¹⁵⁶ skin sensor.

Another very visible application where the implementation of color has accelerated is website imagery presentation. Gaining in awareness is Flat Design 2.0, developed by designer Ryan Allen. This is the next iteration of the vibrantly-colored and grid-friendly approach to website design. Employed are two important techniques: *color blocking* and *colored hover states* (Cao, 2015). Color blocking refers to dividing page content into a grid and applying different colors to create a card-like mosaic (Figure 78). Colored hover states are a subtle animation pattern – as the cursor is moved over each block of content, the color changes to indicate the outcome of the anticipated mouse-click, providing visual feedback to users (del Corral, 2015).

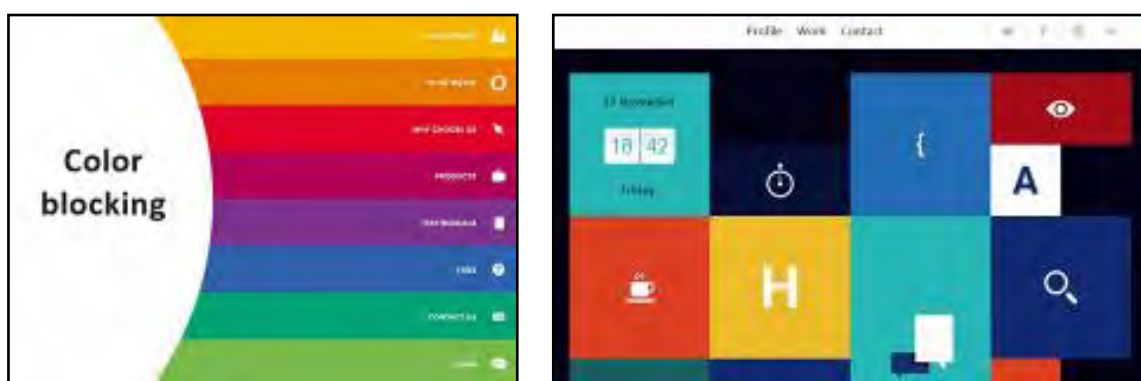


Figure 78. Examples of use of color blocking in website design.

Taking color as an encoding technique to the very smallest level has been achieved with the development of multicolor electron microscopy by the National Institute of General Medical Sciences (NIGMS) at the National Institute of Health (NIH) (Adams et al., 2016). Electron microscopy (EM) is a technique using beams of accelerated electrons to magnify objects up to 10 million times their actual size. Standard EM images are in grayscale, and previously pseudo-color was added post hoc via image enhancing software. Real-color EM employs serial applications of several rare earth metals called lanthanides. Using a type of EM called electron energy-loss spectroscopy that differentiates among the lanthanides by measuring differences in absorption energy levels, a level of detail of cell structure not possible with light microscopy can be obtained via color contrast. Such imaging has many potential applications in biology, e.g., allowing distinction between cellular compartments.

Finally, are advancements and new directions in color measurement (see *Spectroradiometry* section). Measuring perceived color has always been difficult, as color is not a single factor characteristic (see *Color Perception* section). In an attempt to provide a “better quality” of color metrics, the future of colorimetry, at least for reflective surfaces, is to go “beyond color” to measurements that incorporate surface attributes such as texture and gloss. Also on the horizon are new color process automation technologies (cPAT) providing real-time

¹⁵⁶ Photoplethysmography optically obtains volumetric measurement of an organ. Often a pulse oximeter is used, which illuminates the skin and measures changes in light absorption.

color data taken directly from the process stream and sent to a closed-loop color control solution, enabling automatic adjustments based on the colorimetric data received from the color measurement instrument (Pickett, 2014).

Color in Culture and Symbolism

The ability of color to present meaning and/or evoke emotion is well known throughout history (Birren, 1952; Valdez & Mehrabian, 1994; Kaya & Epps, 2010; Kaya, 2004). Color can produce emotions that range from contentment, sympathy, and tranquility, to sadness, anger, and excitement. The significance and impact of color varies widely across peoples of different nations, cultures, and religions. These meanings can be extremely diverse both within and across these categorizations, especially when the context of the usage changes across generations. Many cultural bodies have strong color associations in contemporary society: nations through flags, sports teams through uniforms, corporate brands through logos, and educational institutions through school colors (Schloss, Poggesi, & Palmer, 2011).

Deeply embedded in the cultural meaning associated with color is the use of color as a symbol. A symbol is a conceptual device that stands for, or suggests, an idea, belief, or action. In general, symbolism refers to the use of symbols to represent these ideas and emotions. Symbols are an effective method of communicating information efficiently. Examples include the dove as a symbol of peace, a skull and crossbones for pirates and poison, a crown for power (as in a monarchy), and a heart for love and romance. Color, as a symbol, communicates instantly, conveying information and evoking deeply embedded emotional responses (Stoughton & Conway, 2008). While cultural differences do play a major role in individual responses to symbols and color, some studies have shown a cultural independence in some color emotion models (Ou, Luo, Woodcock, & Wright, 2004).

Symbols are widely used and can take on any form, e.g., text words (letters themselves), numerals, sounds, shapes, pictorials, and colors. Some symbols may be combinations of these forms; for example, the widely used traffic “stop sign” is the symbol that represents the requirement to bring a vehicle to a complete stop. The stop sign incorporates a designated shape (octagon), color (red) and text label (“STOP”).

Color symbolism is defined as the use of color to convey meanings and invoke responses, and it has developed over centuries from cultural, mythical, historical, religious, political, and linguistic associations (Yu, 2014). Many fundamental color symbolisms are drawn from nature, e.g., green symbolizing potency in barren regions and blue representing the sky. These associations between nature and color seem to be universal but with considerable differences across cultures (Hupka, Zaleski, Otto, Reidl, & Tarabrina, 1997).

Combinations of colors can represent new and differing associations. For example, in Western culture, the combination of red and green is strongly associated with the celebration of Christmas and the combination of orange and black with Halloween. Color combinations used in nation flags (e.g., red, white, and blue in the U.S. flag) can evoke strong patriotic responses in citizens (Figure 79). Similarly, in sports around the world, team colors arouse strong emotions in both players and fans alike.

A specific color or color combination often can result in diametrically opposed responses in different individuals. For example, in some traditions, black is the color associated with death and mourning, while in others white is associated with these concepts. Red, the color of blood, is usually linked with living, but it represents death in the Celtic world (Yu, 2014). Green, a color associated with nature and life among many cultures, aroused fear in ancient Egyptians when present in the eyes of cats.



Figure 79. Color combinations in nation flags are examples of color symbolism.

A representative, but abbreviated, list of traditional national, cultural, and religious significances and uses attached to two common colors, “red” and “green,” is presented in Table 11. Even in this limited listing, both the commonality and opposition of the meanings and uses of a specific color become acutely apparent. For example, in China, the color green generally has a positive meaning (e.g., harmony and hope) but can be associated with disgrace in the context of a man being given a green hat, meant as a sign of having an unfaithful wife.

It has been difficult to rigorously correlate emotion with color, not surprising, given the complex nature of color vision and color perception. Cuykendall & Hoffman (2009) attribute three connections between color and emotion: evolution, culture, and experience. The evolution connection is based on survival instinct; colors linked to certain past events trigger certain reactions. The culture link lies in specific associations based on emotionally charged events (e.g., patriot celebrations). The experience connection associates personal experiences with a certain predominant color or color combinations (e.g., discomfort at the color of moldy chesses based on an episode of food poisoning). An extreme emotional association with color is known as chromophobia – fear of color(s). Some sufferers may be afraid of only certain colors or of shades of a specific color (Batchelor, 2000; Doctor, Kahn, & Adamec, 2010).

Much of the past research has looked for correlations between specific emotions and specific CIE color coordinates of the stimuli (Kaiser, 1984; Dunwoody, 1991). However, there is no simple correlation between CIE coordinates and perceived colors, and, hence, no simple correlation between CIE coordinates and emotion (Cuykendall & Hoffman, 2009).

Use of symbolism in aviation.

Since the use of symbolism is universal in coding of information, it is not surprising that it is employed in aviation. Color symbolism has been present in the aviation cockpit for some time, traditionally with yellow and red used for cautions and warnings in instrument displays (Society of Automotive Engineers Aerospace [SAE], 1988; Rash & Manning, 2003). Red is used

Table 11. Traditional cultural meanings and uses of the colors “red” and “green” (Gage, 1993; Madden, Hewett, & Roth, 2000; De Bortoli & Maroto, 2001).

Nation	Significance and common uses	
	Red	Green
China	• Good luck, long life, happiness, prosperity • Summer, fire • Used for weddings, funerals, festive occasions	• Benevolence, health, harmony, hope • Calm, healing, self-assurance • Disgrace
India	• Love, beauty, purity, wealth, energy • Birth, fertility • Worn by brides	• New beginning, happiness. • Harvest, nature • Virtue, hope
United States	• Excitement, passion, hot, spicy • Used for warnings of danger	• Money • Jealousy, envy
Brazil	• Visibility, vibrancy • Associated with auto accidents	• Imperial House of Braganza of Pedro I, the first Emperor
Japan	• Blood, passion, strength, sacrifice	• Youthfulness, freshness
France	• Blood, passion, lust, virility	• Romance (in literature) • Royalist sympathy (during French revolution)
Culture		
Eastern	• Good fortune, posterity, happiness • Worn by brides	• Eternity, family, harmony • Health, peace, posterity
Western	• Passion, anger, power, excitement • Stop • Hot • Used for warnings of danger • Fire, blood, war • Valentine’s day	• Nature • Misfortune, jealousy, envy • Vigor, spring, fertility • Greed • St. Patrick’s Day
Religion		
Buddhism	• Life force, preservation, fire, and sacred things or places	• Balance, harmony • Nature, trees, plants
Christianity	• Sacrifice, passion, love	• Rest, life, growth • Triumph of life over death
Hinduism	• Happiness, wedding elements	• Life, peace, happiness
Judaism	• Life • Sin, joy, happiness • Scarlet and crimson have been used to symbolize blood	• Plant life, natural growth • Being fruitful • Maturity • Disease (in Leviticus)
Islam	• Danger, war	• Color of garments, cushions, and carpets in paradise • Color of Mohammed’s coat • Flag color

to warn the pilot of a hazardous condition or when a system (or some portion of a system) that affects safety of flight is inoperative, and some critical corrective action or override is required. Examples of indicators that employ red include “Fire” and “Fuel Low.” Flashing red is used to warn of emergency conditions that require urgent action by the pilot to avert serious impending damage or injury. Yellow is used to caution a pilot a condition that may affect the successful continuation of the flight requires attention. Examples include “Autopilot out” and “Radar out.” FAA Advisory Circular (AC) 120-76C, *Electronic Flight Displays* (FAA, 2014b), states consistent use and standardization for red and amber (or yellow) is necessary to retain the effectiveness of flight crew alerts. A common presentation is the progression from green to amber to red, representing increasing degrees of potential hazard or safety criticality, and needing for response. The colors used in a cockpit are usually well-regulated, adhering to an industry standard. When cockpit and display designers don’t adhere to standards, pilots may be faced with a color scheme that conflicts with experience and habit (Novacek, 2003). Inconsistencies in the use of color should be evaluated to ensure color choices are not susceptible to confusion or errors, and do not adversely impact the intended function (FAA, 2014b).

In addition to the red-yellow alert colors, two colors equally prevalent in the cockpit are green and white. Green, which has a long-standing cultural significance in the Western countries, is used to indicate the active status and satisfactory operation of a monitored system (e.g., “Pitot Heat”). White is used to indicate system conditions not having correct or incorrect implications (e.g., selection of the “Intercom” system). White, against a black background, is commonly used on MFDs to present graphics and indices that simulate the cluster dial displays (e.g., altimeter, vertical speed, and course indicator) (Figure 80) of previous generation cockpit designs. The introduction and proliferation of MFDs serving as moving maps and PFDs have increased the number of colors (e.g., magenta and cyan) now present in modern cockpits (see *Flight instrument panels* section).

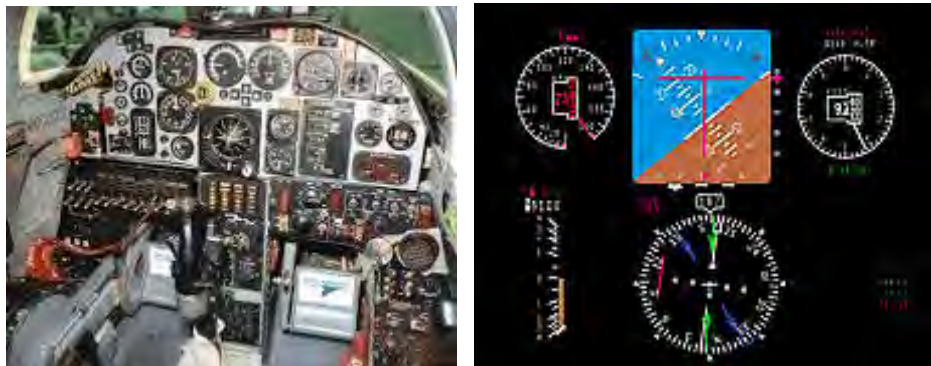


Figure 80. Use of white color to simulate previous generation cluster dials (left) on modern MFDs (right).

Regardless of the form (or combination of forms) embedded in a symbol, its interpretation by an observer is based on context and the observer’s experience, which includes cultural, national, and religious influences. In the cockpit, color (when sufficient contrast is present) is just one form of a symbol that may reduce the time it takes for a pilot to locate and identify a switch, button, or handle. However, because of the impact of user experience, virtually all symbols may present increased ambiguity as compared to text labels (McDougall & Osborne,

2006). One of the basic tenets of good man-machine interface HF design is to reduce ambiguity in the meaning of a symbol (which includes the use of color symbolism). Therefore, in cockpit design, it is important color choices in the labeling of handles, switches, buttons, etc., not introduce any additional uncertainty.

As globalization produces increased interaction and integration of trade and information across peoples, nations, and cultures, a greater awareness of the differences in the meanings and uses of color must be recognized and considered (Smith-Jackson & Wogalter, 2000). If a specific set of colors is employed in an application or system design, developers must be aware of how users will react to and interpret those colors and color combinations. This is especially important if an application or system is intended for users of a different culture (or for a global audience). It is generally accepted culture influences schema development, and therefore, attitudes, perceptions, and decision-making (Shade, 1989; Han & Shavit, 1994). Culture is considered a manifestation of shared experiences, which facilitates communication within similar cultures but interferes with communication across different cultures (Romney & Moore, 1998; Perez-Arce, 1999; Smith-Jackson & Wogalter, 2000). Although difficult to study due to the number of variables that define a culture, a cultural bias in color use and symbolism can be very powerful, and unintended consequences in safety-driven environments such as aviation may result if cultural differences are ignored. Fortunately, in general, there has been considerable effort placed in recent years on “standardization” or “harmonization” of design rules, especially since aircraft are sold internationally by most large aircraft companies.

Most of the above discussion has focused on the diversity of color meanings and uses across cultural, national, and religious boundaries. However, there is the potential for additional differences in these classifications within cultures and nations based on demographics. Specifically, numerous studies have shown gender and age to affect color perception, preference, and association (De Bortoli & Maroto, 2001; Khouw, 2003; Arthur, Johnson, & Young, 2007; Ou, Luo, Sun, Hu, & Chen, 2012). There is evidence some color preference changes are responses to life experiences, especially activities and experiences having color(s) as a central attribute, e.g., school colors (Terwogt & Hoeksma, 1995; Adler, 1999).

The wide-spread use of the internet today for both social and commercial interaction has prompted considerable HF research into the selection and use of colors and color combinations in website design. However, little of this research has been directed into sub- and cross-cultural effects (Cyr, Head, & Larios, 2010).

Gender differences in color preference.

While the underlying principles are not well understood, humans show strong likes and dislikes for particular colors (Jonauskaitė et al., 2016). These preferences also have a gender element. While some early studies (1800s-1930s) (Dorcus, 1926; St. George, 1938) showing gender preference differences suffered from a lack of control over illuminant source specifications (Boiano et al., 2006), Eysenck's (1941) work showing gender differences in color preferences generally has been supported by more modern studies (Bregman & Geuens, 2004; Ling, Hurlbert, & Robinson, 2006). Radeloff (1990) found women are more responsive to the use of color and are more likely than men to have a favorite color. Women show a preference for

more subdued colors, in contrast to men's preference for brighter colors. M. Babolhavaeji, M. A. Vakilian, & A. Slambolchi (2015) in a discussion of marketing approaches to differences in gender-based color preferences state women are affected more than men by the color choices used in advertising and product-packaging. Their review of consumer behavior studies concluded blue color should be used for men-oriented advertising and product packing; women prefer purple color; and blue and green colors are the best choices for products intended for both men and women (Ellis & Ficek, 2001; Zentner, 2001). These recommendations are in agreement with a survey of (self-selected) internet users conducted by J. Hallock (2003) that produced distributions of favorite color preferences for all survey respondents, as well as by gender (Figure 81).

In a study of college students, Green (1995) showed women to have a more sophisticated color discrimination capability. Subjects were asked to identify the colors of 21 color chips. The results showed women recognized significantly more elaborate colors than did men. Findings suggested gender differences in color identification may be attributed to a difference in the socialization¹⁵⁷ of men and women.

Age differences in color preference.

Virtually all color vision theories accept changes in color perception occur during a lifetime: the ability to see colors gradually lessens with age (Scheffrin & Werner, 1993) (see *Anatomy and Physiology of Color Vision* section). However, many of these theories do include an adaptation mechanism for retaining consistent color appearance over the aging process (Werner, 1998). While these age-related changes in perception are most pronounced in later years, changes in color preferences can change slowly or abruptly, affected by experiences.

Birren (1961) found color preferences, and hence color responses, vary by age. Even as infants, humans appear to show color preferences, apparently for the hues of blue, purple, and red (Zemach, Chang, & Teller, 2006). While blue and red maintain a high preference throughout life, with age other colors become more preferred. Birren (1961) states, "With maturity comes a greater liking for hues of shorter wavelength (blue, green, and purple) than for hues of longer wave length (red, orange, and yellow)." The results of Birren's age-related "favorite color" preference survey are presented graphically in Figure 82 (Hallock, 2003).

M. M. Terwogt and J. B. Hoeksma (1995) conducted a study on colors and emotions with regards to preferences and combinations, noting that as people get older, their preferences are likely to change as a result of social and cultural influences. They state, "As children grow up they learn that the expression of anger is often punished. They also learn that the color black (within Western culture) is associated with mourning." The authors also state the effects of color preferences are still present at later stages of life, but these preferences are outweighed by additional (unidentified) factors.

¹⁵⁷ Sociologists define gender *socialization* as the process of learning the social expectations and attitudes associated with one's sex. Gender socialization is used to explain why men and women behave in different ways.

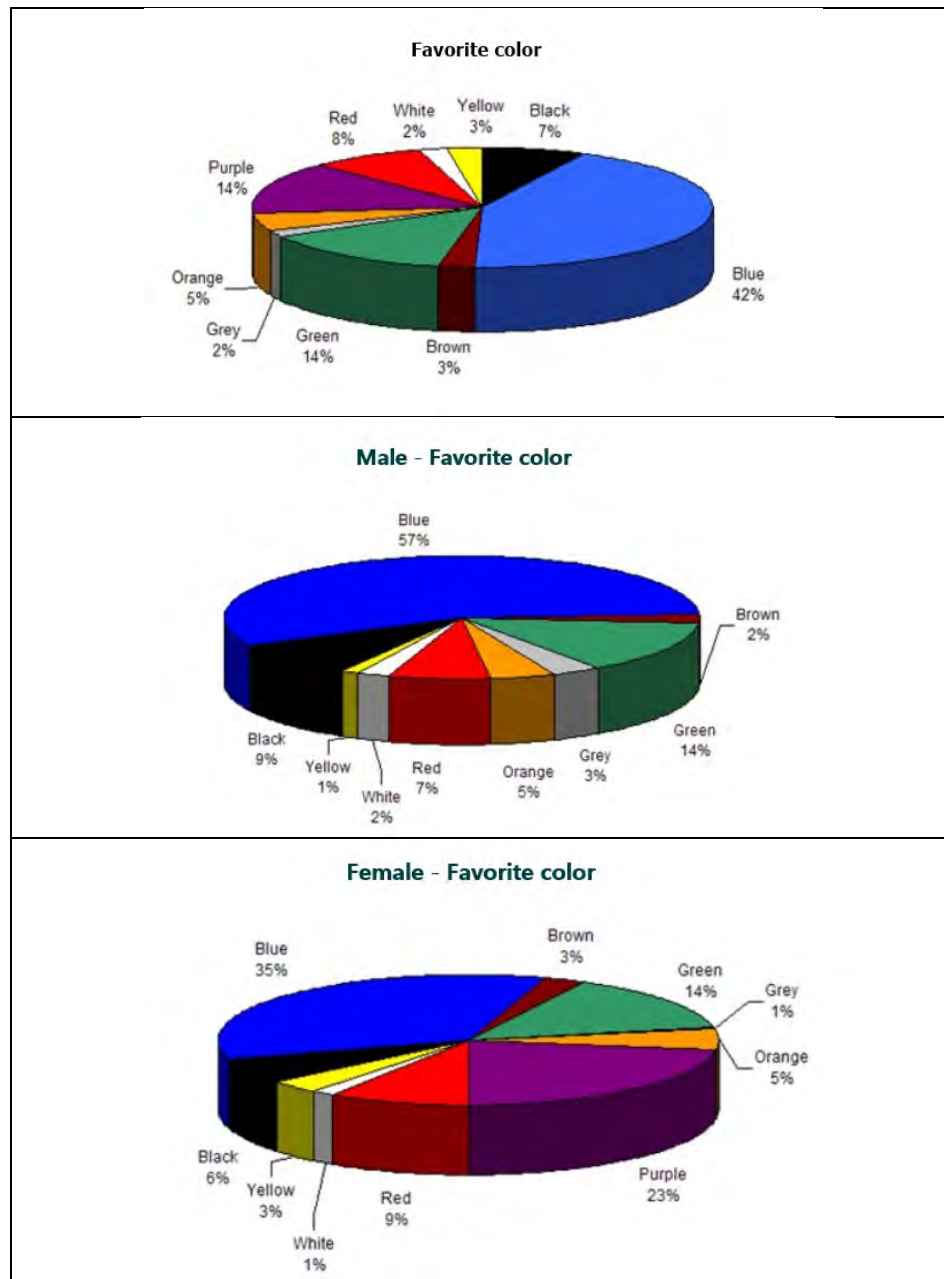


Figure 81. Favorite color preferences for all survey respondents (top), as well as by gender (middle and bottom) (adapted from Hallock, 2003).

In a more recent study, researchers conducted two experiments to investigate the effects of aging on color emotion and preference; in both experiments, subjects had a bi-modal (young-old) age distribution (Ou, Luo, Sun, Hu, & Chen, 2012). In the first experiment, subjects were presented 30 monochromatic (single-color) samples one-at-a-time and asked to describe the color by choosing one descriptor from each of four word pair scales: warm/cool, heavy/light, active/passive, and like/dislike. In the second experiment, 190 pairs of samples were presented. A fifth word pair, harmonious/disharmonious, was added to the four scales used in the first experiment. The experimental results showed for single colors (Experiment 1), all color samples

were rated as less active, less liked, and cooler by the older subjects than by the younger subjects. For color pairs (Experiment 2), light color pairs were rated as less active and cooler by the older subjects; achromatic color pairs and pairs consisting of colors in similar chroma were rated as cooler, less liked, and less harmonious by older subjects than by younger.

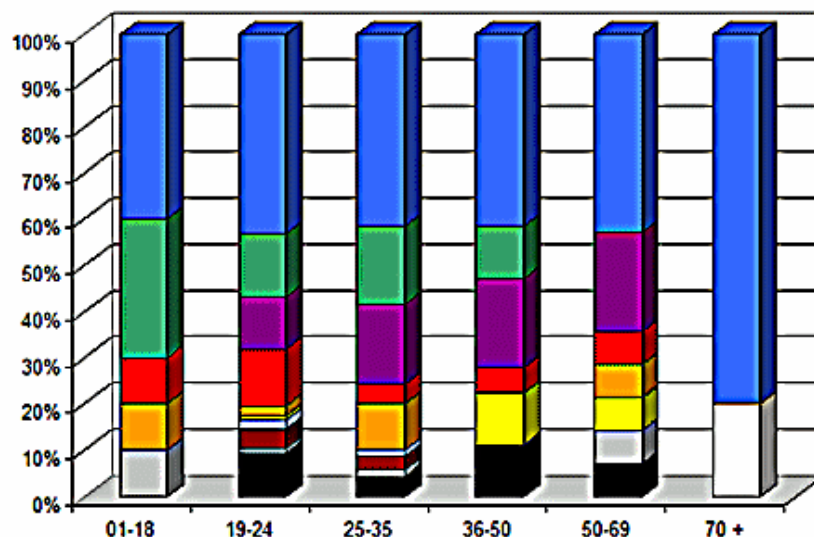


Figure 82. Favorite color preferences by age group (adapted from Hallock, 2003).

Color in Aviation

To this point, a number of fundamental concepts of color have been presented. These concepts have included origin mechanisms; characteristic principal properties; measurement methodology and instrumentation; important scientific, artistic, and technological milestones in the human use of color for both esthetic and practical purposes (e.g., art and information coding, respectively); and gender and age differences in human color preferences. Having established a necessary foundation for appreciating the expansive and all-invasive presence of color, the role of this special characteristic of virtually all visual perceptions now can be considered in aviation applications, with emphasis on U.S. Army rotary-wing aircraft. The approach is to begin with a brief overview of the use of color in aviation in its most evident applications, lighting and markings. This is followed by an obligatory, but essential, look at the external use of color, not just its use on the exterior of aircraft in the form of lighting and exit markings, but also as used in airport runway lighting and obstacle beacons. Emphasis will be placed on exterior marking and labeling of door and window exits, both in civil and U.S. Army aviation. Next, some common examples of color use inside aircraft are described. This is followed by a discussion of the use of color in cockpit instrument panels. While this discussion will introduce the color-rich digital instrumentation now in U.S. Army aviation, a more in-depth look at individual cockpits is presented in the *Color in U.S. Army Rotary-Wing Crew Stations* section. The section will close with a review of color in aviation charts and maps, one of the first uses of color in the cockpit.

Color is used in aviation (general, commercial, and military) for coding of signals and information presentation (Menu et al., 2001). Signal coding primarily refers to external/exterior lighting, which includes beacons and navigation lights on aircraft, obstruction warning lighting,

runway and taxiway lighting, approach lighting, and parking guidance systems, as well as lighting and labeling on aircraft and airport operations/service/support vehicles (Federal Aviation Administration [FAA], 2010). Use of color for information presentation ranges from the labelling of emergency exit handles and switches to cockpit instrument panels, controls, and switches (including MFDs). Color also is used as a major feature discriminator on maps and charts (Kumagai, Williams, & Kline, 2005; Gibb, Gray, & Scharff, 2010).

As a general guide to colors used in aviation (inside and outside the cockpit), the following examples are provided (adapted from Civil Aviation Authority (CAA) Paper 2006/04, *Minimum Colour Vision Requirements for Professional Flight Crew – Part 2*) with additional applications from Brookes (2015):

- Anti-collision beacons and strobes are red or white.
- Navigation lights are red, green and white.
- Rotating/flashing beacons on ground emergency vehicles are red and/or blue.
- Airport ground support vehicles have amber rotating beacons in addition to the normal red. Vehicles also have the normal rear and brake lights as well as amber turn lights and white reversing lights.
- Red, amber, white, green, and blue lights are used on runways, taxiways and parking areas.
- Obstruction lights are usually red.
- Visual landing aids may include red, amber, yellow, green and white lights.
- Conventional panel instruments often carry colored numerals, arcs and sectors, typically red, yellow, white, green or red. Sometimes a blue line is used on small twin-engine general aviation aircraft to indicate best climb speed for an engine-out condition
- Attitude and directional indicators may have brown and blue hemispheres.
- Annunciator panels, i.e. panels conveying messages, may have red warnings and amber cautions.
- Electronic Flight Instrument Systems (EFIS) displays may use white, red, green, amber, blue, and magenta colors, as well as sometimes brown, yellow, blue-green, violet, purple, pink and mauve.
- Aviation maps often are printed in four or more colors including brown, amber, yellow, green, blue, and purple. The advent of electronic map displays brings a wide range of colors into the cockpit.
- Visual Approach Slope Indicating (VASI) Systems are typically color-coded. An example is the Precision Approach Path Indicator (PAPI),¹⁵⁸ which uses red and white lights to indicate the aircraft position relative to a defined glide-slope angle.
- Specialized color usage in aviation lighting may be encountered, e.g., F/A-18 Advanced Multi-Purpose Color Displays (AMPCD) missile icons, Air Traffic Control (ATC) Tower Light Gun Signals, and Fresnel lenses (used on aircraft carriers and naval air stations).

¹⁵⁸ The *PAPI* is a light array positioned beside the runway. It normally consists of four equally-spaced lights color-coded to provide a visual indication of an aircraft's position relative to the designated glide slope for the runway. The PAPI system provides additional glide slope information than the VASI.

Exterior use of color.

The lights on the exterior of aircraft fall into two general categories. The first is navigation (position) lights or beacons that are always illuminated while the aircraft is in operation; a second type includes takeoff and landing lights used to improve visibility when the aircraft is close to or on the ground. Aircraft navigation lights consist of a red light located on the *left* wingtip's leading edge and a green light on the *right* wingtip's leading edge (Figure 83). Additionally, a white navigation light is located as far aft as possible on the tail or each wing tip. High-intensity strobe (anti-collision) beacons are located on the aircraft to aid in collision avoidance. These are located near the center of the fuselage, on both top and bottom, and must project light 360° around the aircraft's vertical axis. Commercial aircraft employ high intensity "wing inspection lighting" for assessing wing ice accumulation at night. FAA Federal Aviation Regulations (FARs),¹⁵⁹ specifically FAR 91.205, address operational lighting requirements for all civil registered aircraft. FAR 23 paragraphs 1381-1401 define certification requirements for normal utility, acrobatic, and commuter category aircraft. Likewise, certification requirements for transport category and rotary-wing aircraft lighting are covered under Parts 25 and 29, respectively, under the same paragraph designations (1381-1401).

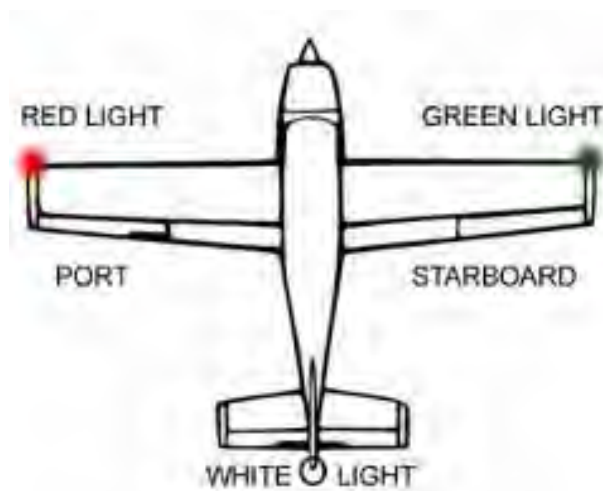


Figure 83. Positions of navigation lights on aircraft.

In The Code of Federal Regulation (CFR) 14 CFR 23.1397 (Government Printing Office, 2002a),¹⁶⁰ three specific colors are defined: aviation red, aviation green, and aviation white. These colors are defined by a set of CIE x,y,z chromaticity coordinates (Table 12). Aviation red is orange-red to deep red in appearance. Aviation green peaks between 495 nm and 534 nm. Aviation white is based on the allowable colors provided by tungsten filament lamps that approach blackbody radiators; the FAA allows white from very orange 1800 °K to 5000 °K.

For civil aviation airport approach lighting systems, color is used in the VASI (red and white; or amber, green, and red) or the PAPI (red and white) lighting systems. One PAPI system

¹⁵⁹ The *Federal Aviation Regulations* (FARs) are rules prescribed by the Federal Aviation Administration (FAA) governing all aviation activities in the United States. The FARs are part of Title 14 of the Code of Federal Regulations (CFR). These rules frequently are referred to as "FARs" but specific parts/sections officially are referred to as "14 CFR part XX.XXX" (e.g., 14 CFR 91.205).

¹⁶⁰ There are identical corresponding color specifications sections in 14 CFR Part 25, 27, and 29, *Airworthiness Standards*.

uses a combination of four lights in a single row, normally on the left side of the runway, to provide the pilot with more specific information about the approach of the aircraft relative to the ideal glide path (Figure 84). When the aircraft is on the glide path, two white and two red lights are presented. Other combinations indicate deviations in the glide path, either higher or lower.

Table 12. CIE chromaticity specifications for FAA-defined aviation red-green-white.

Aviation red	Aviation green	Aviation white
y is not greater than 0.335; and z is not greater than 0.002.	x is not greater than 0.440-0.320 y ; x is not greater than y -0.170; and y is not less than 0.390-0.170 x .	x is not less than 0.300 and not greater than 0.540; y is not less than x -0.040; or y_0 -0.010, whichever is the smaller;* and y is not greater than x +0.020 nor 0.636-0.400 x ; * y_0 is the y coordinate of the Planckian radiator for the value of x considered.

For marking runways, red, white, green, blue, and yellow lights may be employed. The lights marking the end of a runway are red. Some airports use a centerline lighting system of lights to assist landing in adverse weather conditions. Several configurations are used, but in general they are spaced at 50-foot intervals along the runway centerline. When viewed from the landing threshold, the runway centerline lights are white until the last 3,000 feet of the runway. The white lights begin to alternate with red for the next 2,000 feet, and for the last 1,000 feet of the runway, all centerline lights are red. Taxiway centerline lead-off lights are color-coded green and yellow to warn pilots of the runway environment. Omnidirectional taxiway lights outline the edges of the taxiway and are blue in color. Obstructions are marked or red lighted to warn pilots of their presence during daytime and nighttime conditions. Obstruction lighting can be found both on and off an airport to identify obstructions. They may be marked or lighted in any of the following conditions (FAA, 2008):

- Red obstruction lights – that flash or emit a steady red color during nighttime operations, and the obstructions are painted orange and white for daytime operations; or
- High intensity white obstruction lights – that flash high intensity white lights during the daytime with the intensity reduced for nighttime;
- Dual lighting – a combination of flashing red beacons and steady red lights for nighttime operation, and high intensity white lights for daytime operations.

Color also is used in airport beacons operating between dusk and dawn to help pilots identify airport types (Figure 85) (FAA, 2008):

- Flashing white and green for civilian land airports;
- Flashing white and yellow for a water airport;
- Flashing white, yellow, and green for a heliport; and
- Two quick white flashes alternating with a green flash identifying a military airport.



Figure 84. The Precision Approach Path Indicator (PAPI) system (FAA, 2008).

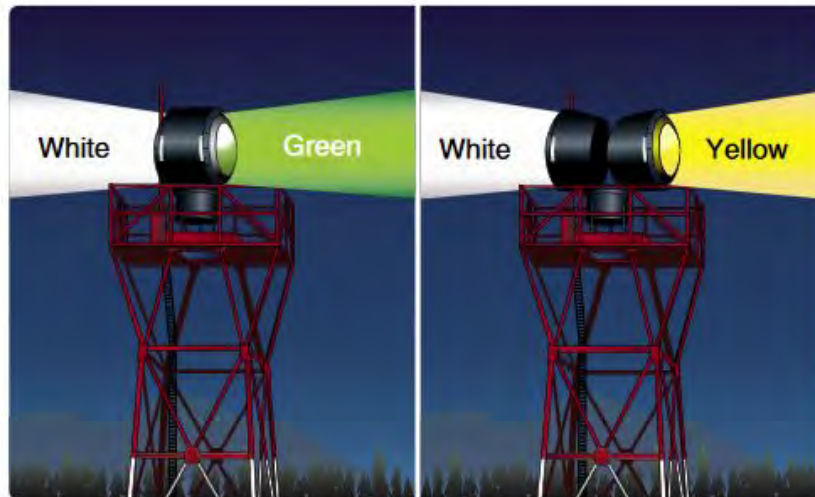


Figure 85. Airport beacons at civilian land (left) and water airports (right) (FAA, 2008).

Medium and high intensity red and white lights (static and flashing) are used as warnings for collision avoidance (anti-collision) on tall structures, e.g., radio and television transmitting towers, industrial cranes, and wind turbines). FAA AC No. 70/7460-1L (FAA, 2017a) provides standards for marking and lighting obstructions deemed to be a hazard to navigable airspace. Various requirements/recommendations are provided for lighting of obstructions reaching or exceeding 150-foot (46-meter), 200-foot (61-meter), 499-foot (152-meter), and 700-foot (213-meter) levels above ground level (AGL).

The military follows FAA requirements but often applies additional restrictions and/or requirements. General provisions and criteria for planning, designing, and constructing lighting systems for U.S. Army airfields, heliports, and helipads are provided in TM 5-811-5, *Technical Manual, Army Aviation Lighting* (Department of the Army, 1991).

Color also is used in specific exterior labels (markings). Multiple FAA regulations (FARs) refer to use of color for labels/markings both outside and inside aircraft. One exterior example is the FAR 25 and FAR 121 requirement that transport¹⁶¹ aircraft have a 2-inch colored band outlining side fuselage exits that are required to be openable from the outside (important in the event of the need of rescue workers to access the aircraft in emergency situations) (Figure 86). While a specific color is not defined, its size and contrast with the background are. Regulation 14 CFR 25.811 (Government Printing Office, 2002b) states in the case of exits other than those in the side of the fuselage, such as ventral or tail-cone exits, the external means of opening, including instructions if applicable, must be conspicuously marked in red, or bright chrome yellow if the background color is such that red is inconspicuous.



Figure 86. Example of colored band outlining side fuselage exit door on transport aircraft.

Exterior emergency markings for U.S. Army aircraft.

The marking of U.S. Army aircraft emergency egress exits¹⁶² also have exterior marking and labeling to assist rescue workers responding to crash scenes in opening doors/canopies to extract pilots and other crewmembers. Requirements for these markings are given in TM 1-1500-345-23, *Technical Manual, Painting and Marking of Army Aircraft* (Department of the Army, 2015a). The requirement is that exterior markings identifying escape hatches, doors, and exits be yellow on dark surfaces or black on light surfaces. Figure 87 shows the U.S. Army's TH-67 Creek training helicopter¹⁶³ with black outlines on exits.

For the purpose of reducing detection in operational environments, U.S. Army tactical aircraft (i.e., UH-60 Blackhawk, CH-47 Chinook, and AH-64 Apache, (Figure 88) [also see

¹⁶¹ Transport category is defined by the FAA as carrying people and cargo.

¹⁶² The terms *ingress* and *egress* are generally military terms referring to the processes of entering and exiting the aircraft, respectively. The phrase *emergency egress* refers to the actions performed by the crew member to quickly and rapidly exit the aircraft during emergency situations.

¹⁶³ Beginning in 2016, the TH-67 Creek is being replaced by the UH-72 Lakota as the U.S. Army's training helicopter.

Current U.S. Army Cockpits section]) use North Atlantic Treaty Organization (NATO) symbol color Black #37038 or #37030.¹⁶⁴



Figure 87. Black emergency egress markings on the U.S. Army TH-67 Creek training helicopter.



Figure 88. U.S. Army tactical aircraft: UH-60 Blackhawk (left), CH-47 Chinook (middle), and AH-64 Apache (right).

The UH-60M Blackhawk cargo door windows that can serve as rescue panels are each marked with four black right-angle corner bands centered equidistant from the center of the window panel (Figure 89, right).¹⁶⁵ The exterior pilot and copilot door handles are labeled in black to indicate “LOCKED,” “CLOSED,” and “OPEN” positions (Figure 89, left); cargo doors have a “OPEN” and “CLOSED & LOCKED” labeling.

For emergency entrance to the cockpit, the CH-47F Chinook cockpit is equipped with jettison doors (handles located at the center of each door), which are labeled in black “DOOR JETTISON/PUSH TRIGGER/TURN HANDLE DOWN” (Figure 90, left). Emergency entrance to the cargo compartment is through the right side cabin door, upper cabin door escape hatch, and/or cutout panels. Similar to the UH-60M Blackhawk, CH-47F windows have four black

¹⁶⁴ NATO symbol colors are defined in Army Regulation/Fuels and Lubricants Standardization Policy for Equipment Design, Operation, and Logistics Support (AR 70-12) (Department of the Army, 2015b).

¹⁶⁵ Comprehensive crash rescue information about U.S. aircraft can be obtained at the U.S. Army Combat/Readiness Center (USACRC), Fort Rucker, AL, website: <https://safety.army.mil>

right-angle corner bands (Figure 90, middle). Each side of the aircraft has a cut-out rescue area labeled in black “CUT HERE FOR EMERGENCY RESCUE” (Figure 90, right).



Figure 89. Pilot/copilot door handle exterior labels (left) and rescue panel corner markings (right) on the UH-60M Blackhawk.



Figure 90. Exterior emergency markings on the CH-47F Chinook: jettison cockpit door (left); window right-angle corner markings (middle); and cut away rescue hatch (right).

AH-64D Apache exterior emergency egress markings are located on the top of the aircraft's nose section just in front of the copilot/gunner cockpit (Figure 91, left). These markings consist of three black label boxes, each with arrows pointing to the jettison handle access door. The smallest box is labeled “PUSH TO OPEN;” the two largest boxes are labeled “CANOPY JETTISON HANDLE/REMOVE PIN BEFORE FLIGHT/JETTISON PROCEDURE/ROTATE HANDLE 90° AND PUSH IN.” The boxes and lettering are originally painted black. However, due to weathering, these labels can present a blue-gray appearance (Figure 91, right, top). The standard canopy handle on the AH-64D Apache is located on the starboard side of the aircraft and is labeled “OPEN” and “CLOSED.” Again, the original color is black, but fades to a blue-gray color with weathering (Figure 91, right, bottom). An additional marking relating to the emergency canopy jettison consists of black triangle labeled “EXPLOSIVE DEVICE/CANOPY JETTISON” on top and “DANGER” on each side.



Figure 91. AH-64 Apache exterior markings for the emergency Canopy Jettison Handle (left), their blue-gray appearance following weathering (top, right), and the standard canopy handle (bottom, right).

Exterior lighting for U.S. Army aircraft.

As with civil aviation aircraft, exterior lighting on Army aircraft provides visual indications to other aircraft for the purposes of navigation and safety. Multi-aircraft formation flying, which is almost exclusively a military maneuver, requires an additional and specialized group of exterior lighting known as formation lights. Additionally, tactical aircraft may employ low intensity strip lighting as a supplementary visual aid for night formation flight.

Military aircraft, in general, meet FAA directed lighting requirements. However, the military may request exemptions from specific aircraft lights sections of FARs 27, 29, and 91. One area for exemption for the U.S. Army has been for exterior lighting compatibility with night imaging systems (e.g., I² devices such as ANVIS), especially in formation flight where aircraft red (port/left) and white (starboard/rear) position lights in the past have severely degraded pilot visual performance with night imaging devices (Snook, Rash, & Colbert, 1993). This has been, and remains, a tri-service problem for rotary-wing aviation (Kinney & Simpson, 1992) (see *Night imaging technology in Army aviation* and *Crew station lighting* sections).

UH-60M Blackhawk.

Figure 92 depicts the exterior lighting system for the UH-60M. Position lights on the UH-60M are outboard of the right and left landing gear support (Items 1 and 2, respectively) and on the top tail pylon (Item 3). The lights are green on the right, red on the left, and white on the tail; adjacent to each of these visible position lights is an IR emitter position light (not shown in figure). Formation lights for the UH-60M are located on top of the main pylon cowlings, tail drive shaft cover, and horizontal stabilator (Item 4). The system consists of four green EL lights

(commonly referred to as *Slime* lights) and four collocated IR emitters (Department of the Army, 2009).

Anti-collision lights on the UH-60M are four strobes in two separate units, one beneath the aft fuselage and one on top of the aft pylon section (Figure 92, Item 5). Additional exterior lighting consists of the cargo hook well area EL lighting (not shown in figure), a landing light (Item 6), and a controllable dual element searchlight with normal and IR capability (Item 7). The searchlight is mounted on the *right* bottom of the nose section; the 600-watt landing light is mounted on the *left* side beneath the nose section.

Figures 93 and 94 show photographs depicting positions of various exterior lights on the UH-60M Blackhawk.

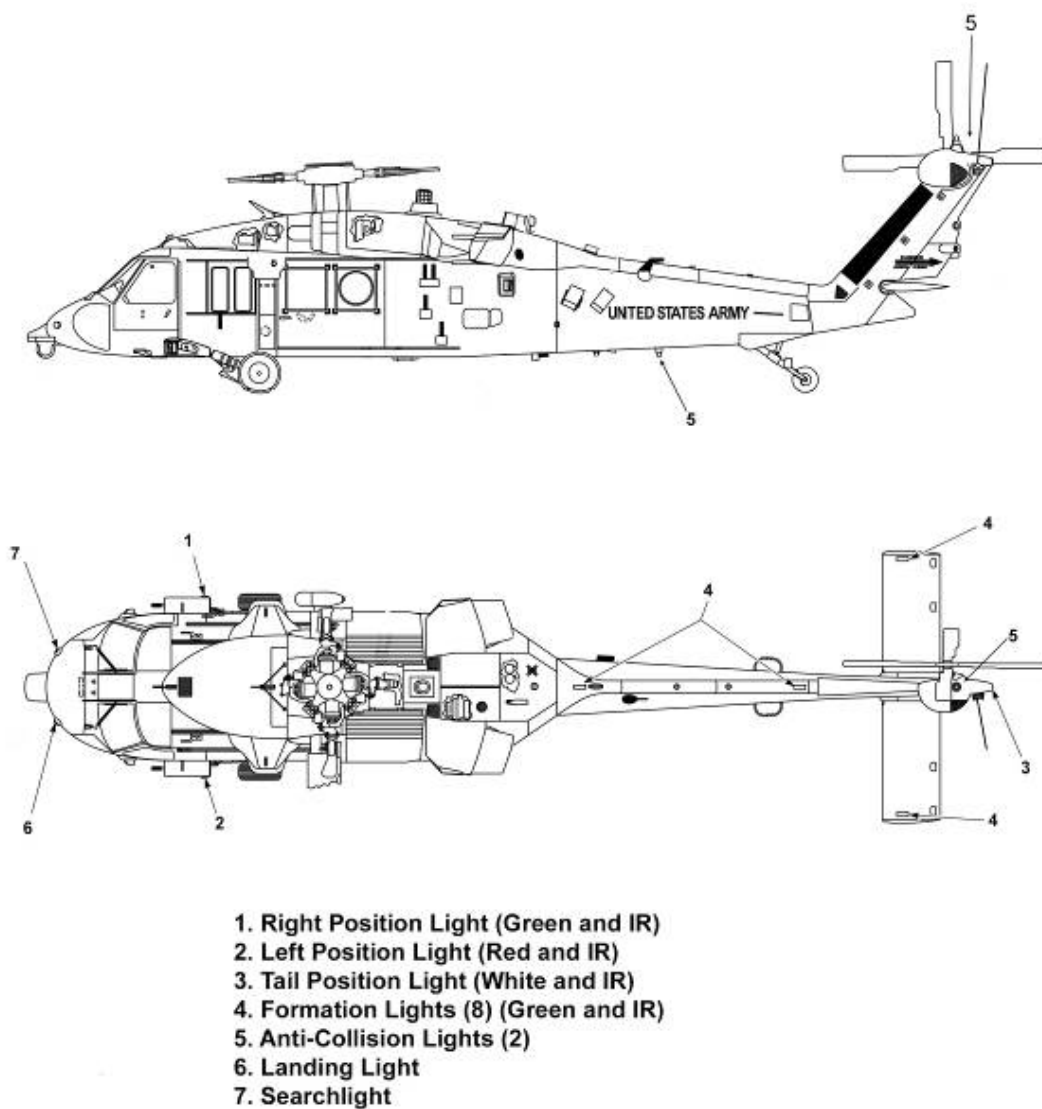


Figure 92. Exterior lighting on the UH-60M Blackhawk (Department of the Army, 2009).



Figure 93. UH-60 Blackhawks lined up for formation flight, showing some position, formation, and anti-collision lights.



Figure 94. Green and red position lights on UH-60 Blackhawk.

CH-47F Chinook.

The exterior lighting system of the CH-47F is depicted in Figure 95 (Department of the Army, 2013). The CH-47F has three position lights: green on the right side of the fuselage, red on the left side, and white on the aft pylon (Items 1, 6, and 4, respectively). Formation lights include five EL panels for unaided night operations and eight ANVIS-compatible lights. Three of the EL panels form an equilateral triangle located aft of the forward pylon (Item 2); the other two panels are on the top of the aft pylon (Item 5), aft of the top anti-collision light (Item 3). The ANVIS-compatible formation lights are located on each side of the forward pylon; two on each side of the fuselage; and two on the aft pylon (one aft of the anti-collision light and one on the vertical panel at the rear of the aft pylon (Item 8).

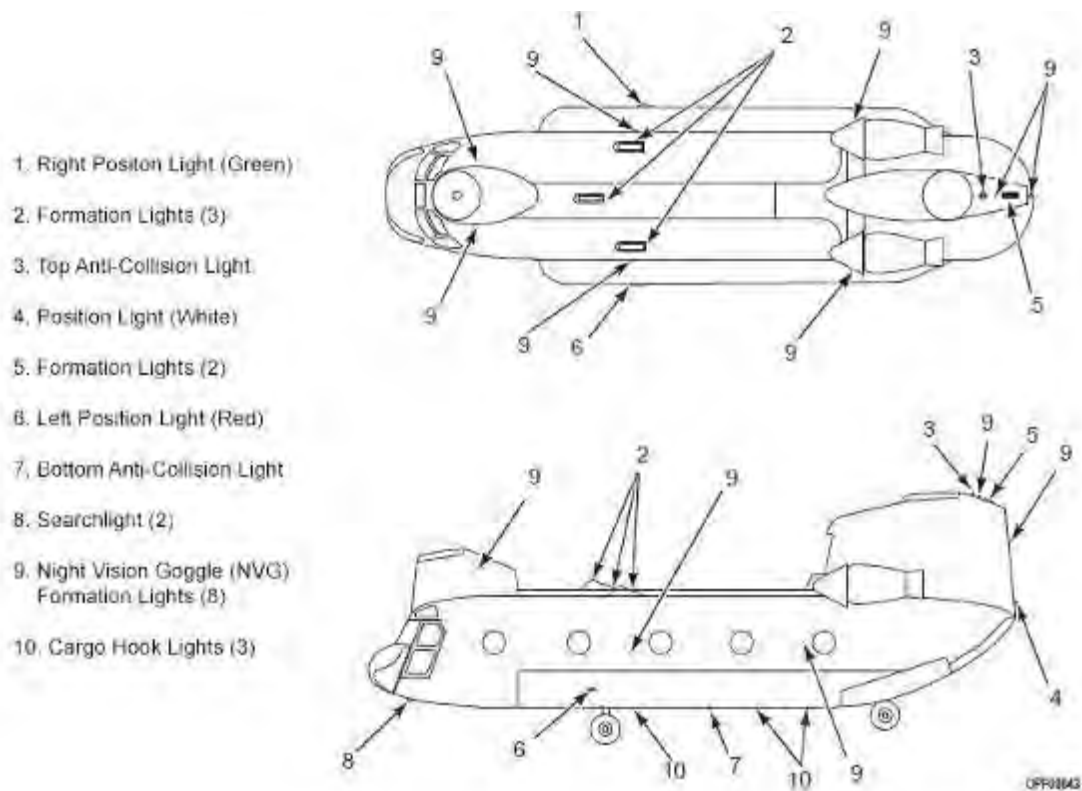


Figure 95. Exterior lighting on the CH-47F Chinook (Department of the Army, 2013).

There are two red anti-collision strobe lights on the CH-47F: one is located on top of the aft pylon, and the other is located on the underside of the fuselage (Figure 95, Items 3 and 7, respectively). Additionally, there are two IR anti-collision lights, one on top of the aft pylon beneath the red anti-collision light and one on the fuselage underside beneath the red anti-collision light. Both the pilot and the copilot have searchlights, each with two white visible lamps and three IR LED lamps (Items 8). Three ANVIS-compatible lights are located on the bottom of the fuselage (Item 10). These lights are directed toward the forward, center, and aft cargo-hooks and provide extra lighting during night external load operations.

Two views of a CH-47F Chinook through the ANVIS, showing the nose-mounted searchlight, tail-mounted anti-collision light, and/or position lights are presented in Figure 96.



Figure 96. CH-47F Chinook viewed at night through ANVIS. (Department of Defense photos)

AH-64D Apache.

Exterior lighting on the AH-64D consists of formation, position, and anti-collision lights, as well as a search/landing light (Figure 97) (Department of the Army, 2015c). Four green formation lights (Item 4) are located on the upper surface of each wing, the upper centerline of the aft fuselage, and on the upper surface of the vertical stabilizer. Position lights include one green light on the right engine nacelle, one red light on the left engine nacelle (Item 3), and one white light aft on the top aft side of the vertical stabilizer (Item 2). High intensity red and white anti-collision strobe lights are located on each engine nacelle (Item 5). The searchlight provides omnidirectional search and landing illumination during low visibility conditions and is located under the forward section of the right Extended Forward Avionics Bays (EFAB), just forward of the landing gear (Item 1).

With the U.S. Army's decision not to pursue the development of the RAH-66 Comanche scout/attack helicopter, the AH-64D Apache program instituted an upgrade program, designated the AH-64E Apache Guardian, formerly referred to as the AH-64D Block III upgrade. Major features of the upgrade include improved digital connectivity, the Joint Tactical Radio System (JTRS), more powerful engines, capability to control unmanned aerial vehicles (UAVs), new composite rotor blades, and LED exterior lighting (which replaces older incandescent lighting). Figure 98 shows an AH-64D Block II Apache with incandescent position lights and a Block III upgraded aircraft with LED position lights (top, port; middle, starboard; bottom, tail).

Interior use of color.

With the exception of the use of color for esthetic purposes in the interiors of aircraft (not an issue for military aircraft), most non-instrument panel interior use of color involves signs and placards, which provide utility, regulatory, and safety information to both aircrew (and passengers in civil and commercial aircraft). For example, the FAA provides a detailed description of the use of a red arrow marking and labeling to identify emergency exit locking

mechanisms (14 CFR 25.811, Emergency exit marking) (Government Printing Office, 2002b) (Figure 99):¹⁶⁶

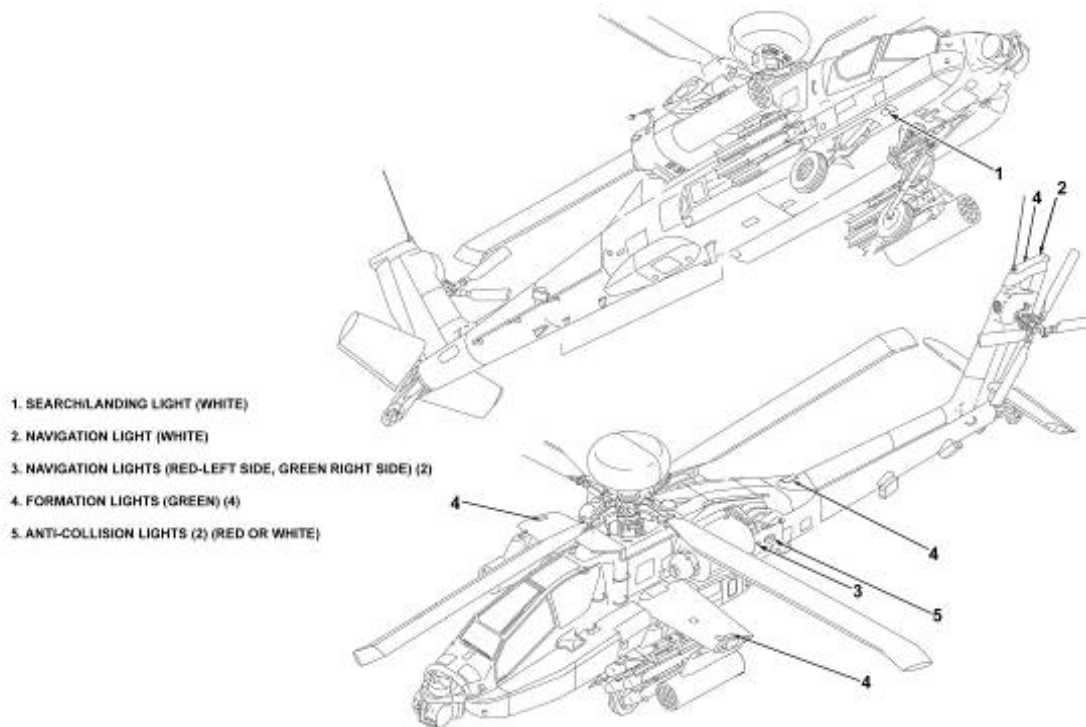


Figure 97. Exterior lighting on the AH-64D Longbow Apache (Department of the Army, 2015c).

With a red arrow, with a shaft at least three-fourths of an inch wide and a head twice the width of the shaft, extending along at least 70 degrees of arc at a radius approximately equal to three-fourths of the handle length. And,

With the word “open” in red letters 1 inch high, placed horizontally near the head of the arrow.

Another example references emergency lighting signs (14 CFR 25.812, Emergency lighting) (Government Printing Office, 2002c):

Each required passenger emergency exit locator and exit marking sign must have red letters at least 1-1/2 inches high on an illuminated white background...

¹⁶⁶ Emergency exits also require exterior markings. Each passenger emergency exit and the means of opening that exit from the outside must be marked on the outside of the aircraft. There must be a 2-inch colored band outlining each passenger emergency exit on the side of the fuselage. Each outside marking, including the band, must be readily distinguishable from the surrounding fuselage area by contrast in color (14 CFR 121.310, Additional emergency equipment) (Government Printing Office, 2016).



Block II red incandescent

Block III red LED



Block II green incandescent

Block III green LED



Block II white incandescent



Block III white LED

Figure 98. Incandescent and LED position lights on AH-64D (left) and AH-64D Block III (AH-64E) Apache.



Figure 99. Examples of emergency exit locking mechanism marking and emergency exit locator sign in passenger aircraft.

In U.S. Army helicopters, emergency exit release handles are yellow and black striped. In the UH-60M Blackhawk, the two cockpit doors are equipped with an emergency release handle for door assembly jettison (Figure 100, top, left); each cabin door has two jettisonable windows with individual release handles (Figure 100, top, right).

The CH-47F has pilot and copilot jettisonable doors. Each door consists of a sliding and fixed window in the upper half and a fixed window in the lower half. A handle is provided near the center of each door assembly for jettisoning the door from inside the helicopter (Figure 100, middle, left). The cargo door at the aft end of the cargo compartment is jettisonable via the RAMP EMER control switch to provide an emergency exit. There is also a cargo window release (Figure 100, middle, right).

The AH-64D has jettisonable canopies. The yellow-black striped emergency handles are located in both the pilot and copilot crew stations and incorporate a safety pin which is to be removed before flight (Figure 100, bottom, left). Canopy jettison is accomplished by turning the handle 90°, releasing, and pushing in. There is also a stores (armament) jettison panel. Pressing the recessed color-striped JETT pushbutton will cause armed stores to be jettisoned (Figure 100, bottom, right).

Color also has been employed for coding of control levers/knobs in the cockpit. In older cockpits, green also was used to indicate landing gear position. “Three Green” was the callout when on approach and the landing gear was safely down. Red was used to indicate an “in transit” condition or disagreement between the position of the landing gear handle and the landing gear. In modern cockpits, “in transit” conditions may be indicated by a series of black and white diagonal slashes in the spaces for landing gear position until the gear is fully down and locked – whereupon the display looks like tires, in white or green. Typically in modern general aviation piston engine aircraft where multiple controls are used for engine and propeller systems, the power (throttle) levers/knobs are black, the propeller controls are blue, and the air/fuel mixture control (used during ascents and descents, as well as to start and shut down the engine) are red



Figure 100. Emergency exit release handles: UH-60M cockpit door (top, left) and cabin window (top, right); CH-47F cockpit door (middle, left) and window ramp (middle, right); and AH-64D canopy jettison (bottom, left) and stores jettison (bottom, right).

(Figure 101). The throttle, propeller, and mixture knobs also may be shaped differently so as to reinforce the visual and tactile association (R. Ranaudo, personal communication, September 30, 2016). The FAA's AC 120-76C, *Electronic Flight Displays* (FAA, 2014b), states if color is used for coding, at least one additional distinct coding method should be used (e.g., size, shape, location). Normal aging of the eye can reduce the ability to sharply focus on red objects, or discriminate blue from green. For pilots with such a deficiency, the visual workload may be unacceptably increased unless symbology is coded in more dimensions than color alone (FAA, 2014b).



Figure 101. Color coding of engine controls in piston engine aircraft.

Interior lighting.

Color is inherent in interior cockpit and cabin lighting of today's aircraft. In civil aviation, most interior cabin lighting is white and used for both general and emergency illumination. Types of light sources vary greatly across aircraft. Overhead lighting typically has been achieved via "cool" white florescent lamps; incandescent and halogen bulbs also have been used. However, LED lights rapidly are becoming standard replacements for cabin dome, floor, and special task lighting. LED lights offer a full range of colors. Although adequate cabin lighting is necessary for both crew and passenger comfort and safety, there are no mandated requirements for passenger cabin lighting. Fortunately, aircraft and lighting manufacturers have recognized the brightness and color of lighting are critical elements of the aircraft interior. LED lighting in modern aircraft has created new opportunities to use color to influence passenger ambience (Slutsken, 2016; Erie Aviation, Inc., 2017). Lighting systems with specific colors and intensities are being tailored to different phases of a flight (primarily in commercial aviation).

The FAA does set requirements for emergency cabin lighting, which can be found in 14 CFR 25.812 (*Emergency lighting*) (Government printing Office, 2002c). However, the emergency lighting requirement is limited to specifying average illumination level (e.g., not less than 0.05 foot-candle (fc) at seat armrest height along the centerline of main passenger aisle(s) and cross aisle(s) at 40-inch intervals) and a minimum illumination at each 40-inch interval of not less than 0.01 fc.¹⁶⁷ Color is not addressed in the general or emergency cabin lighting requirements; as noted above, cabin lighting is universally white.

Interior lighting has the purpose of providing sufficient illumination for pilots and crew to correctly perform all necessary tasks. In the past, floodlighting has been the primary approach to illuminating the cockpit area and flight instruments during night or other low illumination

¹⁶⁷ A foot-candle (fc) is a unit of illumination equal to that given by a source of one candela at a distance of one foot (equivalent to one lumen per square foot or 10.764 lux [lx]).

situations.¹⁶⁸ But, floodlighting often leads to some parts of the cockpit being completely in shadow or insufficiently illuminated (Cooke & Fitzpatrick, 2009). In addition to an adequate level of illumination in all necessary areas, two other important lighting considerations are control and balance. Control refers to the ability to adjust the intensity (level) of the illumination in a given area if needed. This can be crucial when an aircraft is operating in a wide range of illumination conditions. Balance refers to having an equal level of illumination across the entire area of interest. An imbalance can produce situations where the brightest instrument may be at the correct level, but the dimmest is unreadable; or where the dimmest is readable, but the brightest is distracting. Integral lighting in modern MFD cockpits can do much to address the problem of insufficient lighting in an area lit by floodlights but still requiring attention to control and balance.

UH-60M Blackhawk.

The UH-60M interior lighting system consists of cockpit dome and utility lights. ANVIS-compatible blue-green or white lighting can be selected for both of these cockpit lights. Three dome lights are provided for cabin lighting. Two blue-green and two white cockpit floodlights provide secondary lighting for the cockpit and are located on the upper console floodlight panel. The pilot's and copilot's utility light are portable, with coiled cords, and are attached to each side of the upper console. These lights may be adjusted on their mounting to direct the light beam or may be removed and used portably. The utility lights are controlled by a rheostat or a pushbutton on the end of the casting. The lens casting can be rotated to change from white to blue-green and/or spot to flood. There is also a utility light located at the right side of the copilot's seat which can be adjusted for additional illumination of the lower console during night flight.

The UH-60M also has three cabin dome lights that are provided for interior cabin lighting. Each light contains ANVIS blue-green lamps that can be selected individually. There also is electroluminescent ANVIS-compatible lighting in the cargo hook well area to aid in external operations.

CH-47F Chinook.

Interior lighting for the CH-47F cockpit consists of overhead panel lights, center console lights, dome lights, floodlights, utility lights, cabin and ramp lights, emergency exit lighting, and cargo hook lights, as well as pilot, copilot, and center instrument panel lights (which is expanded upon in the *Flight instrument panels* and *U.S. Army Cockpits* sections). All lighting is ANVIS-compatible unless otherwise noted.

The overhead switch panel has integral lighting that adjustable from dim to bright. Lighting is provided for all control panels on the center console. The Control Display Units (CDUs) on the canted console have integral lighting control for the display areas.

Two cockpit dome lights are attached to the overhead structure. Each dome light contains a white lamp and a blue-green ANVIS filtered lamp. Twelve floodlights provide a secondary

¹⁶⁸ Many cockpits, commercial and military, have had a floodlight system known as "thunderstorm lights." Pilots were instructed to turn these lights on if thunderstorms were present in the immediate area at night, as associated lightning could flash blind a dark-adapted pilot (R. Ranaudo, personal communication, March 6, 2017).

source of light. Nine of these are in the cockpit with seven located under the glareshield¹⁶⁹ and two on the cockpit bulkhead. The cockpit also has five stalk lights.¹⁷⁰ Two are on the outboard glareshield; one troop commander stalk light is at the aft end of the center console; and there is a stalk light on each of the power distribution panels (PDPs), which are located behind the pilot and copilot.

Two utility lights, connected to individual flexible cords, are mounted in retaining sockets on either side of the overhead switch panel above the pilot and copilot. The lights are detachable and can be moved about to meet special lighting needs.

The CH-47F has five cargo compartment/cabin and ramp lights attached to the overhead structure (Figure 102, left). Each light contains ANVIS blue-green and white lamps that can be selected individually. Three emergency exit lights are in the cargo compartment near each of the three primary emergency exits: the main cabin door, the emergency exit opposite the main cabin door, and the ramp emergency exit. These lights illuminate whenever a loss of power on the essential bus occurs or during a landing when 3 to 5g are exceeded as sensed by an inertia switch. There is also a mounted emergency lamp (Figure 102, right)



Figure 102. Example of CH-47F overhead dome light (left) and emergency light (right) in the cargo compartment.

Three external ANVIS-compatible cargo hook lights are located along the bottom of the fuselage. These lights are directed toward the forward, center, and aft cargo hooks for the purpose of providing extra lighting during night external-load operations.

Two emergency jump light boxes are located in the cargo compartment. Each box has an electric bell in the center with a red light fixture on one side and a green light fixture on the other side. The jump lights are used to notify the flight engineer during airborne delivery operations and to alert the troop commander during paratroop drop missions.

¹⁶⁹ A *glareshield* is a screen attached to the cockpit canopy of an aircraft to reduce the effects of glare.

¹⁷⁰ As the name implies, a *stalk light* is a light source located at the end of a stalk-like arm, which can be bend and twisted to change the direction of the light's illumination.

AH-64D Apache.

The AH-64D interior lighting system provides crewmembers with ANVIS-compatible lighting and includes: primary, flood/emergency, signal, and standby instrument lighting. Each crew station also has one utility light. Primary lighting consists of illuminated light plates, display bezels, and keypads. Emergency lighting consists of floodlights to provide crew station illumination if needed. Signal lighting includes warning, caution, and advisory indicators/-switches. Standby instrument lighting provides illumination of the four standby flight instruments in the pilot station. A utility light is stowed on the left side of each crew station; they are hand-held lights with a coiled cord. The color of the utility light illumination can be adjusted to white or ANVIS-compatible blue-green (see *Night imaging technology in Army aviation* and *Crew station lighting* sections). Also, see the *Fight instrument panels* and *Current U.S. Army Cockpits* sections for expanded descriptions of crew station use of color and color lighting in specific U.S. Army helicopters.

Whether it is in commercial or military aircraft, interior lighting in the cockpit and/or rear cabins is rapidly changing as lighting technologies accelerate (Adams, 2005). Standard incandescent lamps ruled for decades.¹⁷¹ Challenged briefly in the 1990s by the halogen lamp (a technology allowing tungsten to be redeposited on the lamp's filament, thereby extending its life), the incandescent lamp recently has relinquished its prominence to the solid-state LED. While the LED's advantages of low power consumption, increased reliability, and flexibility in color and brightness are well-known, it has an additional characteristic giving the incandescent lamp an advantage in aviation applications: it does not have a filament that can weaken in the vibration and temperature extremes present in the aviation environment, an especially advantageous feature in rotary-wing military aircraft, known for their multi-axis vibrational modes.

Flight instrument panels.

Wickens (2003) describes flying an aircraft as having to perform four tasks of decreasing priority: *aviate* (keeping the aircraft airborne); *navigate* (moving from point to point), sometimes along a predetermined route, while avoiding hazards of terrain, weather, other traffic, and vulnerability (in combat); *communicate* (internally and externally); and *manage systems*. All of these tasks are integrally tied to cockpit displays, which include flight instruments, radios, armament, and imaging systems.

Flight instrument panels are what provide the pilot with information about the flight situation of the aircraft. While there are six primary types of information required by the pilot, i.e., altitude, attitude, airspeed, vertical speed, heading, and turn and bank direction), other aircraft status instruments are present that deliver useful and frequently critical information, e.g., fuel level, engine torque, oil pressure. This flight information was delivered on early flight displays mostly via dial pointers. Modern display panels use numerical (digital) indicators, symbols, and graphics. While more pronounced in modern instruments, even in older flight instruments, color has been used as a method of coding information into the displays.

¹⁷¹ Although florescent lighting dominated passenger cabins in private and commercial aircraft.

It is well recognized the increased use of color displays in aircraft crew stations offers distinct advantages and disadvantages (Widdel & Post, 1992; Derefeldt et al., 1998). Historically, monochromatic displays, with resolution, luminance, and contrast levels exceeding most color systems at the time, required less design effort and analysis on the part of engineers to yield suitable display designs and formats (Walrath & Hunter, 1990). The capability for extensive color coding available in today's color display technologies provides an opportunity for enhanced crew task performance, but only if color is used selectively and wisely.

There is a difference between *basic task* performance such as using the PFD to fly an instrument approach, and *skilled* performance, which is the integration of the basic flight task with mission objectives. Testing with pilot subjects has shown color does not have much impact on basic task performance when comparing monochrome vs. color displays. However, color can greatly improve skilled performance (better attention and situation awareness) when the pilot is performing flight tasks within a mission objective, such as finding a target on an MFD or using the PFD for delivering the ordinance on a target. Another example is in a modern transport aircraft. The instrument landing system (ILS) guidance cues on the head-down display (HDD) are in color, but usually the head-up display (HUD) cues which are identical, are monochrome. The FAA requirement is that the two displays must be identical in form and function – except for color enhancement, where presumably task performance will be the same with either display. But it is the MFDs in these aircraft that provide enhanced attention and situation awareness with respect to surrounding weather conditions, other air traffic, aircraft systems operation, and geographical location – essentially skilled performance. The use of color enhances attention and situation awareness and supports skilled performance, which is the goal in modern flight systems.

Its misuse, however, can degrade performance over the simpler and now mostly abandoned monochromatic display. Color discrimination is difficult in reduced illumination environments and for individuals with color deficiencies; color is a more challenging technique for representing continuous data (e.g., weather map); color may cause confusion when inconsistent with experience or stereotype color schemes; and the irrelevant use of color for aesthetics may interfere with color coding.

Color in tasks.

The performance enhancement that color brings to flight displays is it being a highly effective method for coding visual information elements, making it easier to find and identify information on a display. For example, in search and identification tasks, when compared to a monochrome (e.g., B/W or grayscale) display, use of color can increase the identification speed by as much as 200% (if the color of the target is unique for that target and is known in advance) (Christ, 1975). However, a majority of flight instruments and displays have, as their major function, the presentation of aircraft status and mission flight information. Much of these data presentation can be considered as data labeling, in which color is used to present text, numbers, and symbols (although color can be used as a location feature).

But text labeling is not the only application of color on displays. Xing (2006a,b) cites three additional major tasks or roles where color is known to improve performance: attention,

segmentation, and identification. While not limited to cockpit displays, their relationships to color usage are instructive in understanding color perception and its impact on visual performance.

Attention.

Color is a well-known technique for calling attention to an object in a visual scene (i.e., feature cuing). This attention technique is one of a group of “visual pop-out effects.” An image detail can appear more prominent when one or more of its features (e.g., size, shape, luminance, texture, orientation, motion, or color) differ significantly from the background (surrounds) (Treisman & Gelade, 1980; Vazquez, Gevers, Lucassen, van de Weijer, & Baldrich, 2010).¹⁷² These techniques to draw attention depend on a bottom-up process, meaning they depend only on the pattern of stimulation falling on the photoreceptors (i.e., stimulus rather than task-driven). Studies investigating saliency maps show color, contrast, and orientation are among the most relevant features in initial scanning of a visual scene (Parkhurst, Law, & Niebur, 2002; Goldstein, 2006). However, Goldstein (2006) points out attention is not based only on feature saliency. Cognitive factors such as prior scene knowledge, the nature of the visual task, and past experience can override the initial effects of salient features in visual scanning and determine fixation.

Nonetheless, color (specifically hue) is a strong pop-out technique. In the left box in Figure 103, a randomly positioned set of similar characters are presented: multiple “T”s (erect and inverted), two “L”s and two “I”s. The task of finding (searching for) the “L”s and “I”s is not difficult; but, it is time consuming. In the middle box in Figure 103, the “L”s and “I”s have been coded red and magenta, respectively, greatly decreasing the needed search time to locate. However, this effect has limitations. In the right box of Figure 103, the advantage of the color “pop-out” effect is lessened by the presence of additional color-coded subsets (National Aeronautics and Space Administration [NASA] Ames Research Center, 2000a).

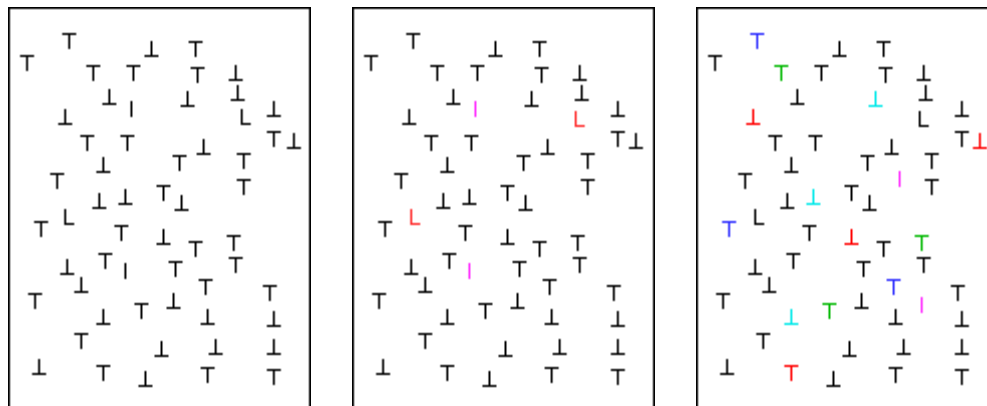


Figure 103. Use of color coding as a “pop-out” effect. (Image credit: NASA)

¹⁷² In the field of visual perception, a pop-out is a visual scheme that draws attention to or sets out a specific element from an otherwise homogeneous background (Mibulumukini, 2015). Color, shape, temporal modulation (flashing), and high contrast (bolding) are examples of such schemes.

While based on research specifically related to natural (jungle) scenes, Frey et al. (2011) found the axis of red-green color (chromatic) contrast plays the largest role in attracting attention in some natural scenes, while the effects of a blue-yellow color contrast are much less influential. This was in agreement with Wirz's (2005) study for natural rainforest scenes; however, feature detection by color contrast is not restricted to natural environments.

In display-based scanning tasks, certain colors – red, closely followed by yellow and green – and certain color combinations (i.e., color contrast) have been found to have more saliency than others (Osberger & Rohaly, 2001; Drelie-Gelasca, Tomasic, & Ebrahimi, 2005). As a first order explanation for this color ranking, red may be expected to be the most visible color, as the retina has more red-sensitive cones (~64% of the 6 to 7 million cones) (Williamson & Cummins, 1983); conversely, blue would be the least visible due to the retina having the least number of blue-sensitive cones (~2%). However, for displays in the near-visual field, color contrast, not a specific color, is the determining factor (see *Color Perception* section).

Color saturation is another predictor of attention via color. The more saturated an element is in comparison to its surroundings, the more quickly it is likely to be detected. Saturation likely contributes to an object's saliency (Frey, 2004; Willenbocker, 2010). While perhaps not a direct concern for displays, consumer research also has shown the perceived size of objects depends on their color saturation level; specifically, increasing color saturation increases size perception (Hagtvedt & Brasel, 2017). Saturation is the dimension of color that gives it purity; decreasing saturation brings a color closer to a shade of gray (see *Color Science* section). However, it must be understood color saturation's influence on an attention effect remains related to its surroundings (i.e., via color contrast).

In displays and in the visual world in general, *contrast* is the difference between an object (target) and its background that allows a distinction between the two. Visual contrast has two components: luminance (brightness) and color. Luminance contrast is a measure of the luminance difference between two (usually) adjacent areas (e.g., target and background). Luminance contrast can be formulated mathematically and presented in different ways, e.g., contrast, contrast ratio, modulation contrast (Klymenko et al., 1997). The available luminance contrast on a display depends on its luminance range. The range from minimum to maximum luminance values a display can produce is referred to as its dynamic range. Usually the preferred descriptor (or figure-of-merit [FOM]) for the luminance dynamic range within a scene reproduced on an analog CRT display is the number of shades of gray that can be presented between white and black (Figure 104). Shades of gray are luminance steps differing by a defined amount. They are, by convention, defined as differing by the square-root-of-two (approximately 1.414). In modern discrete-element (pixelated) displays, luminance contrast is frequently redefined to indicate the difference in luminance between a fully "on" pixel and a fully "off" pixel (Castellano, 1992). The equation for pixel contrast ratio (C_r) is:

$$C_r = (\text{Luminance of ON pixel})/(\text{Luminance of OFF pixel}).$$

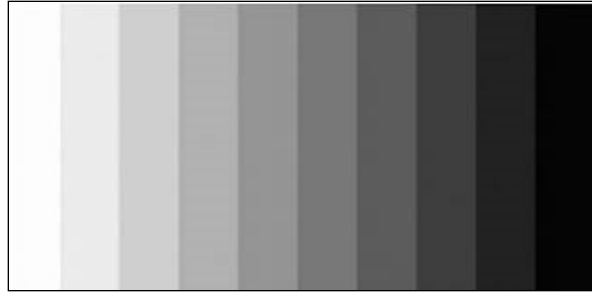


Figure 104. Shades of gray, ranging from white to black on an analog display.

For discrete displays, the shades of gray FOM is replaced by “gray steps” or “gray levels.” For example, a given LCD may be specified by its manufacturer as having 64 gray levels. The uninitiated may misinterpret this as 64 shades of gray, which is incorrect. Its true meaning is the display is capable of producing 64 different electronic signal levels between, and including, the minimum and maximum values, which generally implies 64 luminance levels.

Color contrast is a second component of target/background contrast (extremely important when color is used for text labeling) (Figure 105). Even where the target and background have the same luminance values, images still can be discerned by color differences (color/chromatic contrast). Such equal luminance chromatic contrasts are less distinct in terms of visual acuity than luminance contrasts, but can be very visible under certain conditions (Kaiser, Herzberg, & Boynton, 1971).

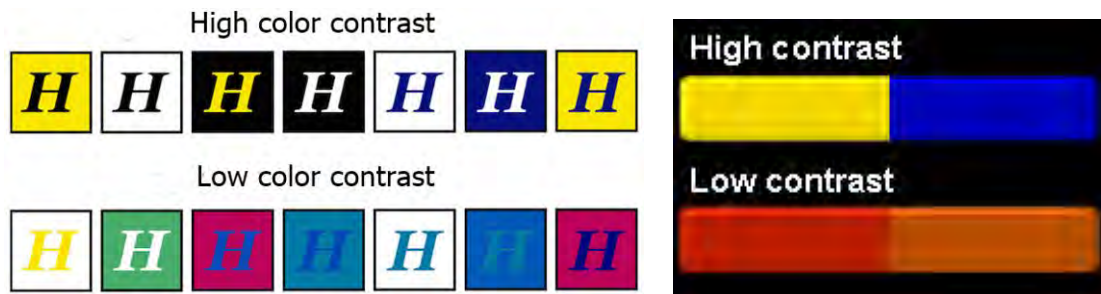


Figure 105. Examples of color (hue) contrast (Source: Texas Tech University).

The sensation of color is dependent not only on the spectral characteristics of the target being viewed, but also on the target’s context and the ambient illumination (Godfrey, 1982). The sensation of color can be decomposed into three dimensions: hue, saturation, and brightness (see *Color properties* section). Hue refers to what is normally meant by color – the subjective “blue, green, or red” appearance. Saturation refers to color purity and is related to the amount of neutral white light mixed with the color. Brightness refers to the perceived intensity of the light. The appearance of color can be affected greatly by the color of adjacent areas, especially if one area is surrounded fully by the other. A colored area will appear brighter, or less gray, if surrounded by a sufficiently large and relatively darker area, but will appear dimmer, or “more” gray, if surrounded by a relatively lighter area (Illuminating Engineering Society [IES] of North

America, 1984). To further complicate matters, hues, saturations, and brightnesses all may undergo shifts in their perceived “values” (see *Color Perception* section).

FOMs defining color contrast are more complicated than those encountered where contrast refers only to differences in luminance. Color contrast metrics must include differences in chromaticity as well as luminance. And, for a number of reasons, it is not as straightforward to transform chromatic differences into just-noticeable differences (JNDs) in a perceived color space. One, color is perceptually a multidimensional variable. The chromatic aspect, or hue, is qualitative and 2D, consisting of a blue-yellow axis and a red-green axis. Additionally, the dimensions of saturation and brightness, as well as other factors such as the size and shape of a stimulus, affect the perceived color and perceived color differences. The nature of the stimulus, whether it is a surface color (i.e., a surface-reflected spectrum) or a self-luminous color (e.g., display) will affect the perceived color space in complex ways. Delineating the nature of perceived color space has been and remains an active area of research with a vast literature (Widdel & Post, 1992).

As a consequence, there is no universally accepted formulation for color contrast, although many have been proposed (Schanda, 2007). One suggested FOM combine contrast due to both luminance and color, known as the discrimination index (ID), was developed by Galves and Brun (1978). The ID is defined as the linear distance between two points (representing the two stimuli) in a photo-colorimetric space. In such a space, each stimulus is represented by three coordinates (U, V, log L). The U and V coordinates are color coordinates defined by the CIE 1960 chromaticity diagram. The third coordinate, log L, is the base ten logarithm of the stimulus luminance. (Note: A concise discussion of the discrimination index is presented in Rash, Monroe, & Verona (1981). The ID is expressed as:

$$D = \sqrt{\left(\frac{\log(L_1/L_2)}{0.15}\right)^2 + \left(\frac{\sqrt{(\Delta U)^2 + (\Delta V)^2}}{0.027}\right)^2}$$

where L_1 and L_2 refer to the luminances of the two stimuli, and (ΔU) and (ΔV) refer to the distances between the colors of the two stimuli in the 1960 CIE 2D color coordinate space. A somewhat more recent FOM, ΔE (Lippert, 1986; Post & Snyder, 1986), combining luminance and color differences into a single overall metric for contrast, was recommended by the International Organization for Standardization (ISO) (1998) for colored symbols on a colored background. It is defined as follows:

$$\Delta E = \sqrt{(155 \Delta L/L_{Max})^2 + (367 \Delta u')^2 + (167 \Delta v')^2}$$

where the differential values (Δ) refer to the luminance (L) and chromaticity (u', v') differences between symbol and background, and L_{Max} refers to the maximum luminance of either symbol or background. Developing the appropriate FOM to describe the color contrast capacities of displays is an ongoing area of development (Widdel & Post, 1992). Most recently, researchers have investigated the possibility of using a metric color space based on the three-component multistage theory of opponent colors when developing on-board aviation displays (Kaziev, Rumyantsev, Sauta, & Shmulevich, 2015). It is suggested the use of metric color space makes it

possible to calculate color contrasts used as the main color characteristics and image-perception indices when constructing display systems of the complexity of avionics displays.

Color contrast is a sufficiently difficult concept when applied to fixed-color, fixed-background displays; it becomes even more complex when applied to HUDs such as in automotive and aviation display applications (Federal Highway Administration, 1998). With HUDs, the background for the symbology is dynamic and can be any color(s); background luminance can range from a fraction of a foot-lambert (fL) to 6,000 fL, depending on conditions. In addition, the symbology is transparent, i.e., the background color and luminance combine with the symbology color and luminance in an additive process, an implication that color contrast would be a meaningless FOM when applied to HUDs (see *Color HMDs* section).

For most aviation displays, user interaction invariably involves readability of text information. For legibility of text on displays using two colors (symbol on background), given sufficient font size, luminance contrast between symbol and background colors is the fundamental factor, with color contrast having a secondary and imprecise impact (Zuffi, Brambilla, Beretta, & Scala, 2007). While display presentations of equiluminant colors can generate high color contrast resulting in legible text, in general, the use of color contrast is not a good strategy in designing text presentation on visual displays. The relationship between color combinations and readability remains elusive even though many different measures of readability and luminance contrast FOMs have been investigated (Hall & Hanna, 2004).

The convolution of contrast (luminance and color) and text readability is demonstrated in Figures 106-108. (NASA, 2000b). Figure 106 presents the full range of luminance combinations possible between a symbol and background. The white at the left edge of the background is the highest possible background luminance (for any color); the black at the right edge is the lowest. No text can have a higher luminance than in the bottom row or a lower luminance than in the top row. Scanning across each row, as the luminance of the text approaches that of the background it becomes illegible (i.e., horizontal band in Figure 106).



Figure 106. Range of possible symbol/background contrasts (NASA, 2000b)

In Figure 107 (top), it becomes apparent that it's not just gray text on gray backgrounds that becomes illegible when luminance contrast is small. The problem extends to colored text, symbols, and backgrounds. Even larger hue differences between the text and background are

inadequate to overcome insufficient luminance contrast (Figure 107, bottom). Here the text colors from the top image are placed on a bright green background.



Figure 107. Examples of illegibility where a large hue difference exists, but luminance contrast is small (NASA Ames Research Center, 2000b).

Blue and yellow can present special legibility problems due to the relatively low visual response to short wavelength (blue) light under typical daytime viewing conditions (see *Anatomy and Physiology of Color Vision* section). While blue-white and blue-yellow combinations produce high legibility ratings, blue-black and yellow-white combinations produce considerable lower legibility ratings (NASA Ames Research Center, 2000b; Karwowski, 2006) (Figure 108). Similar legibility problems occur with other symbol/background combinations differing only in the “blue” channel, e.g., combinations of magenta/red and cyan/green (Figure 109).

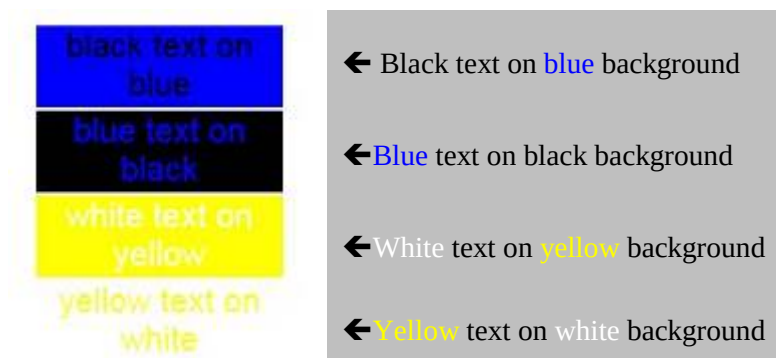


Figure 108. Examples of illegibility of text/background combinations using short wavelength light (NASA, 2000b).

The color contrast discussion was initiated by the fact color can be used to improve performance through the attention process, and contrast plays the primary role. It is important,

however, to carefully separate the use of color (and color contrast) as a “pop-out” effect in quasi-static situations such as the search task presented in Figure 103 (p. 138) or the presentation of colored text, symbols, and graphics vs. its role in situations where color suddenly appears, as with caution and warning lights. The sudden appearance of a “CHECK ENGINE” light on the instrument panel of an automobile or of a “FIRE WARN” or “STALL” warning light in the cockpit grabs attention by a combination of its color coding and its sudden appearance. (Note: In aviation environments, these visual “pop-out” effects almost always are combined with an auditory “pop-out” alert, the combination of which results in a faster response, especially if the pilot’s visual gaze is elsewhere (R. Ranaudo, personal communication, March 16, 2017).

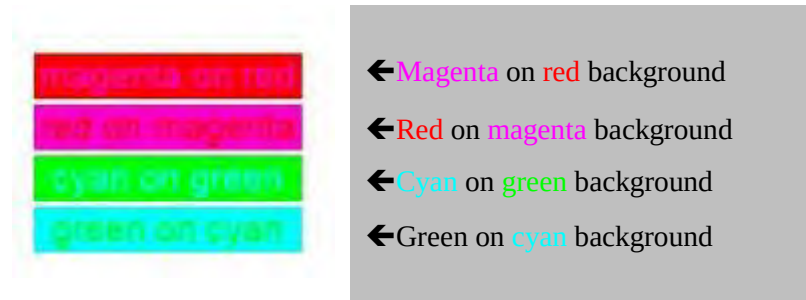


Figure 109. Examples of illegibility where symbol/background combinations differ only in the “blue” channel (NASA Ames Research Center, 2000b).

Segmentation.

The second task where Xing (2006a,b) identifies color use to be advantageous is segmentation. To access the *what* and *where* of particular objects in a visual field, the visual input is organized by a filtering process referred to as segmentation (Pinker, 1984). This process clusters image elements that “belong together.” This involves partitioning and grouping. Partitioning is the dividing of the elements into regions or sequences having coherent internal properties; Grouping is the identification of sets of coherent elements in the image. Basic human visual perception concepts of grouping include various Gestalt principles, e.g., figure-ground articulation, similarity, proximity, and closure (Goldstein, 2005). Segmentation is a critical process in many applications, including image processing and pattern recognition in machine vision (Borsotti, Campadelli, & Schettini, 1998; Cheng, Jiang, Sun, & Wang, 2001).

In implementing segmentation on a display, different colors are used to organize information by segmenting a complex scene into distinctive visual objects (Xing, 2006a,b). A specific color is not necessarily associated with a meaning; it is simply used to join or discern specific data. The use of color for segmentation means data displayed in the same color appear as a visual object separated from other data, assisting a user with where to look for related information. Segmentation is essential when users are faced with cluttered displays and have varying task demands. It has been shown using color segmentation in complex displays is more effective and is processed faster than using achromatic cues (i.e., black, white, and grays) (Treisman & Gelade 1980; Nothdurft, 1993). For color segmentation to be effective (Xing (2006a,b) suggests a number of theoretical and experienced-based conditions regarding luminance ratios/differences and chromaticity differences for the segmentation colors and their

surrounds. One example is that, theoretically, segmentation can be achieved when the chromaticity difference is greater than the color discrimination threshold, which is estimated as 0.004 in CIE uniform chromaticity coordinates. Xing's (2006a,b) work with ATC displays identified non-basic colors in the green-blue domain as good choices for segmentation (e.g., green-blue, gray-blue, and yellowish-green). Smallman & Boynton (1993) found while basic colors do work well, other sets of colors can be chosen that segregate data just as well. They concluded that the critical variable seems to be the sensory difference between the colors, regardless of the named categories in which they fall.

Segmenting a single display into two or more independent areas or inserting a new display area into an existing one is known as windowing, a common term in computer display technology. A high-level use of color segmentation is not too different from the color blocking technique used in website design shown in Figure 78 (p.108).

Identification.

The task of data category identification when data are presented dynamically, intermingled, or distributed in an irregular way on a display can be accomplished by the use of a set of colors (Xing, 2006a,b). In this application, each color is associated with a specific meaning. The effective use of color for identification means searching by color for an item of a given category among many other items can be performed more efficiently and accurately. As with segmentation, the advantage of color over achromatic cues becomes more pronounced as the visual scenes become more complex or the identification task becomes more difficult (Sachtler & Zaidi, 1992).

Recommended conditions for effectively using color in identification tasks include luminance and chromaticity differences (Chen, 1998), as well as guidance on the number and naming of colors (Xing, 2006a,b). Nagy & Sanchez (1992) recommends a luminance difference between colors be less than 20 candela per square meter (cd/m^2) and luminance differences should be minimized so that no one color is much brighter than the others. If the luminance difference between two colors exceeds the 20 cd/m^2 value, an undesirable "pop-out" attention effect can exist. A chromaticity difference between non-basic colors is recommended to be greater than 0.04 in CIE uniform coordinates. The number of colors used to identify data categories is recommended to be fewer than seven, based on work by Carter (1982) demonstrating color has no advantage over achromatic cues for identification when the number of colors used is greater than 6 or 7 and by Cummings, Tsonis, & Xing (2007) that found using more than six colors for identification can result in an increase in errors of omission when users perform multiple tasks.

From the discussion regarding naming of colors across cultures, it was stated 11 basic colors can be reliably and consistently named across populations of different geographic regions and different cultures; these are red, green, yellow, blue, pink, brown, purple, orange, and three achromatic terms, black, white, and gray (Boynton & Olson, 1990). These colors are greatly separated in the color spaces. In addition, magenta and cyan are also among the consistently named colors. Where non-basic colors were suggested for segmentation tasks, studies have demonstrated basic colors work better for identification, especially for data categories in

complex scenes and for complicated tasks (Smallman & Boynton, 1990; Guest & van Laar, 2002).

This section can be summarized by a statement by Taylor (1985): “Colour is important because it can give (organization) to an otherwise complex structure or haphazard configuration, acting to clarify and unify features of the same colour, while increasing the visual (separation) of features in different colours.” This is supported by experimental evidence on the role of color in pre-attentive groupings, perceptual organization, and feature integration (Cahill & Carter, 1976; Treisman, 1982; Bundesen & Pedersen, 1983).

While the rapid advancements in display technologies and improvements in manufacturing capability have overcome some early concerns with the implementation of color coding in aviation displays (i.e., cost), the HF and visual performance studies of its benefits to pilot performance have repeatedly shown that color coding is task specific. Lists of situations where color coding can be most beneficial have consistently included the following (Krebs, Wolf, & Sandvig, 1978):

- Unformatted displays
- High symbol density
- Users must search for relevant information
- Symbol legibility may become degraded
- Logical relationship exists between the color code and user task
- User workload is high

And, a corresponding list for situations where color coding will most likely not be beneficial generally includes (Krebs, Wolf, & Sandvig, 1978; Widdel & Post, 1992; Xing, 2006c):

- Symbol color is irrelevant to the user task and becomes noise
- Symbol color serves as a distractor to the user
- Similarly colored symbols may be visually grouped in non-meaningful ways

Both the benefits of and the recommended constraints on the use of color coding are discussed further in the *Guidelines for Use of Color in Cockpit Displays* section.

Color aviation displays.

In the above discussion, the use of color in displays from a generalized perspective was described. Attention now will be focused on the emergence and application of color in avionics displays. For the last two decades, there has been a trend in aviation to integrate digital technology into the cockpit. One aspect of this trend has been the conversion of the crew station instrument panel from one of a cluster of dedicated instruments to one comprised of one or more MFDs. The use of software and hierarchical paging of information allows multiple configurations of MFDs into any desired instrument, or set of instruments. A MFD integrates the information previously provided by electro-mechanical instruments with the speed and processing power of microprocessors and the adaptability of CRTs and/or flat panel technology

displays. MFDs provide the aircrew access to a variety of data and information, in a near endless array of formats, on a single display (although multiple MFDs may be employed in any given cockpit), and controlled by a single controller interface (Leard, 1999). A single MFD can be configured to provide some or all of the information needed for navigation, communication, system management, and aircraft control. Combined with the background automated monitoring capability of microprocessors, the MFD cockpit offers many advantages. The cockpit design based on MFDs has given rise to the phrase “glass cockpit” (Rash et al., 2001).

While commercial aviation initiated the movement toward glass cockpits, military aviation has been quick in adopting the new digital technologies to include the use of MFDs in the cockpit. At the start, the Army integrated the glass cockpit scheme into four rotary-wing aircraft series: the AH-64 Apache, the UH/MH-60 Blackhawk, the CH/MH-47 Chinook, and the OH-58 Kiowa. The glass cockpit models of these aircraft were designated as the AH-64D, MH-60K, MH-47E, and OH-58D,¹⁷³ respectively. In addition, there were two hybrid¹⁷⁴ crew station configurations that mix MFDs and dedicated instruments, the MH-47D and MH-60L.¹⁷⁵ Today the U.S. Army flies three regular Army models with glass cockpits: the Sikorsky UH-60M Blackhawk, the Boeing CH-47F Chinook, and the Boeing AH-64D Apache (see *Current U.S. Army Cockpits* section).

However, even before the advent of multicolor MFDs in the cockpit, color already was embedded in flight instrumentation, providing important flight data to the pilot. The most used colors were red, orange, yellow, green, and blue, which were easily recognized. Color coding included: red or amber used for cockpit warning/caution lights and green lights used to indicate the position of the landing gear. Blue and brown¹⁷⁶ were used to depict sky and ground, respectively, on attitude indicators. On some instruments, the appearance of a red flag indicated the instrument was not operating properly. A green area on some instruments indicated their normal operating range; whereas, a red area indicated a dangerous operating condition. Interpreting a particular color could be difficult under low levels of illumination and lead to errors.

When insufficient ambient lighting is present, red may appear dark gray in color, and blue may appear as a light gray. Under red lighting, colors lose their identity and appear grayish. For example, light blue, under red illumination, may appear black; yellow might appear reddish white. In general, the greater the variation in the ambient illumination, the lesser the validity the viewer can place in the color coding. Nonetheless, color is still useful and is a mainstay in many fixed flight instruments, e.g., Cessna 172 airspeed, attitude, and heading indicators [Figure 110]). Color can present additional information without added space requirements.

The arrival of the MFD, coupled with greater computing power and speed of solid-state electronics, has brought a dazzling array of lights, colors, and capabilities to the modern cockpit instrument panel. Aircraft flight decks now are a kaleidoscope of data presentations, with an

¹⁷³ The U.S. Army is retiring the OH-58D Kiowa, an armed reconnaissance helicopter, in 2017. An upgraded model, the OH-58F, was developed but not widely fielded.

¹⁷⁴ While glass cockpit models still employ several dedicated instruments, hybrid cockpits (as defined by the aircraft manufacturer) have multiple dedicated instruments and MFDs in a mixed configuration.

¹⁷⁵ The MH designations, e.g., MH-47D and MH-60L, are highly specialized variants of standard Army aircraft series flown exclusively by the U.S. Army's 160th Special Operations Aviation Regiment (SOAR).

¹⁷⁶ In some MFDs (e.g., the U.S. Army's UH-60M Blackhawk), an orange replaces the brown for the representation of the ground.

ever-changing array of visual and audio data. With the increasing use of MFDs that can be preprogrammed or dynamically changed by the selection of one or more button pushes, cognitive scientists warn pilots may have too much information, which can lead to increased workload



Figure 110. Examples of color in fixed cockpit instruments.

and poor decision making (Deveans & Kewley, 2009; Rash, 2013). NASA research pilot R. Ranaudo notes pilots find nothing more frustrating than trying to obtain critical information through a menu architecture requiring multiple button pushes to reach a desired piece of data (personal communication, March 16, 2017).

Imagery from a MFD being used as a PFD configured for the display of critical flight information in a U.S. Army UH-60M Blackhawk is illustrated in Figure 111. Included in the data array (clockwise from upper left) is the airspeed indicator, Attitude Directional Indicator (ADI), barometric altimeter, vertical speed indicator, radar altimeter, Horizontal Situation Indicator (HSI), the Power Pod showing the fuel gauge, and critical engine parameters (e.g., engine revolutions per minute [RPM], rotor RPM, turbine gas temperature, and torque). The display also includes numerous data fields showing information such as the configuration and status of the navigation system, ground speed, wind direction, radio frequencies tuned for each pilot and the position of the stabilator. The imagery presents nine colors: white, black, an orange, and hues of red, green, blue, yellow, magenta, and cyan.



Figure 111. Primary Flight Display (PFD) in U.S. Army's UH-60M Blackhawk, configured for critical flight information.

Besides the orange/ground used for the ground representation and the achromatic colors of black and white, six colors are considered maximally discriminable on displays: a red, a green, a blue, a yellow, a cyan, and a magenta color (Cardosi & Hannon, 1999) (Figure 112) (see *Guidelines for Use of Color in Cockpit Displays* section). Yellows are the result of mixing various proportions of red and green light; cyans are combinations of blue and green light; and magentas are combinations of red and blue. These colors are chosen because they are the ones likely to be the most discriminable, based on their physical differences that correspond to separation in color space. However, precisely how discriminable these colors are will depend upon their precise definition in display producing terms.



Figure 112. Recommended colors for avionics displays (Cardosi & Hannon, 1999).

Specialists in color vision and avionic displays have reached a consensus on some aspects of the use of color in cockpit displays. For example, the earlier SAE (1988) aerospace recommended practice calls for a “conservative and consistent use of color, using no more than six color codes for symbols: red, yellow (amber), green, white, magenta and cyan, while reserving red and yellow for warnings and cautions. Black is used as the display’s background and white for gauge faces, markings, and numbers; blue and brown are for the sky/ground background of the attitude indicator. This brings the recommended maximum of colors to nine if the display background is not included, as given in the 2003 update (SAE International, 2003). The selection of these colors was intended to minimize confusion and to address such factors as color discrimination, search performance (the ability to search for and to locate switches and other items on the instrument panel) and the ability to associate a maximum number of colors with functional attributes.

Color has been a difficult issue for both crew station designer and user communities, especially since newer display technologies have exploded the available color palette. A number of guidelines have been produced, but most lack the sophistication needed to address real-world use of color in the cockpit (see *Guidelines for Use of Color in Cockpit Displays* section). This has been further complicated by the multi-discipline nature of color. Guides tended to focus specifically on HF, functional performance, or operational accuracy, but none are all encompassing. As a result, even the most notable attempts lack definition. For example, a 2013 guide developed by the FAA Civil Aerospace Medical Institute, Oklahoma City, OK, for

evaluating MFD HF, states in its description of color usage (Chamberlain, Heers, Mejdal, Delnegro, & Beringer, 2013):

To maintain effectiveness, color usage should be consistent throughout the MFD and the entire flight deck. Otherwise, confusion and misinterpretation are likely to happen as the flight crew attempts to integrate information across multiple sources both within and outside of the MFD. Colors can be very effective in facilitating information grouping and processing in electronic displays. For color usage to be effective in an MFD, colors must be distinct and meaningful.

All of this is true but lacks specific details. However, the pointing out of the generalization in this guide is not intended as destructive criticism but instead is intended to emphasize the difficulties faced in achieving comprehensive and meaningful color guidelines.

Much of the research involving the integration of color in electronic displays has centered on color discrimination (Kaufmann & Glavin, 1990). However, it is essential that the use of color be based on an overall analysis of hardware, viewing environment, and HF elements of the application. Designers must be aware the perception of complex displayed imagery is governed more by overall interacting characteristics than by individual details. These characteristics include display luminance, ambient illumination range, color selection, information clutter, background, location, viewing angle, color coding scheme, and viewer visual performance, which can be affected by a number of factors, e.g., fatigue, refractive errors, stress, and emotional state (see *Color Perception* section). In summary, the color of cockpit lighting and its intensity should be chosen to ensure flight crewmembers are able to obtain information from instrument panel displays and navigational charts and to perform other visual tasks.

The design of instrument panels based on display characteristics must be accompanied by sound HFE principles. Yeh, Jo, Donovan, & Gabree (2013) have provided a comprehensive checklist of HF regulatory and guidance material for flight deck displays and controls, in the interest of improving aviation safety. This checklist provides guidance on HF issues that need to be considered in the design and evaluation of avionics displays and controls for all types of aircraft (14 CFR parts 23, 25, 27, and 29). Topics include pilot-interface issues of the display hardware, software, alerts/annunciations, and controls, as well as considerations for flight deck design philosophy, intended function, error management, workload, and automation.

Yeh, Jo, Donovan, & Gabree (2013) address color as part of the checklist of considerations and recommended guidance for electronic display information elements and features. Included are general issues of readability, attention or alert capability, and potential error in color interpretation. Guidelines for specific color usage for are presented (e.g., red, yellow, blue). HF issues of color coding, discriminability, consistency, redundancy, and background choice are addressed. A summary of the full checklist is provided in the *Guidelines for Use of Color in Cockpit Displays* section.

Shuttle Atlantis: An illustrative example of color display design.

Perhaps the most intriguing instrument panel and an excellent illustration of adding color to the cockpit was the NASA space shuttle cockpit avionics upgrade known as the Multifunction Electronic Display System (MEDS) glass cockpit implemented in the Shuttle Atlantis in 2000. Scores of outdated CRT displays and electromechanical cockpit instruments/gauges gave way to 11 full-color AMLCD flat-panel screens (Figure 113) (NASA, 2000). While the new technology reduced increasing maintenance costs of the replaced system, the major goals of the redesign were to improve situation awareness, reduce workload, and improve performance (McCandless, Hilty, & McCann, 2005).



Figure 113. Space shuttle Atlantis' MEDS glass cockpit upgrade. (Photo: NASA)

The CRTs in the original shuttle cockpit were monochromatic with all graphics and text being green on a black background. They were reserved for unique displays of trajectory information, guidance, navigation, and control. If a system failed, it was brought up in monochrome on the CRTs, but the crew relied mostly upon the assessment of failures by mission control (R. Ranaudo, personal communication, April 7, 2017). For the updated display formats, the number of colors was ten. A key rationale behind using such a high number was that not all colors appeared on the display format simultaneously, thereby reducing the potential for a cluttered appearance). On most displays, the number of colors is typically no more than six. In addition, not all of the colors applied to dynamic digital data; a number of colors applied to static parameters such as background color and separator lines (McCandless, Hilty, & McCann, 2005). It was concluded the relatively high number of colors aided the crew in differentiating the characteristics of such a complex vehicle, one that operates as a rocket during launch, a spacecraft during orbit, and a glider during entry. The complexity of the systems needed to support these functions imposed large cognitive demands on the crew in order to maintain situation awareness of systems mode and status. A distinct color coding was intended to aid the

crew in maintaining that awareness. The color upgrade produced a more conspicuous display of failures, selections, and pilot inputs (R. Ranaudo, personal communication, April 7, 2017).

A light blue-gray was used for the color of display labels to make them distinctly visible but not as salient as data being driven by a dynamic source, such as main engine chamber pressure, which is normally white. Although green is generally associated with a function being acceptable, the goal for the shuttle displays was to maximize the contrast between the nominal data and the background, even at the expense of violating a general color convention. Therefore, nominal data were presented in white, not green. Magenta was reserved for command messages, such as critical action alerts. Light green was reserved for the display title and navigation.

Four colors were used to represent failure conditions: red, yellow, orange, and cyan. The critical colors of red (warning) and yellow (caution) were used because they corresponded to the conventional meanings for these colors (Krebs, Wolf, & Sandvig, 1978). The purpose of conventional coding for the caution and warning colors was to draw attention rapidly (Stokes & Wickens, 1988). Orange represented a unique condition in which the primary and backup computer systems produced different outputs (e.g., to indicate the primary computer system would control the engine thrust to a different level than the backup computer system). Cyan represented cases in which data were unavailable for display (e.g. a failed sensor).

From the space shuttle to advanced fighter aircraft, the development of avionics systems has historically been a long-term process. As a result, systems either become fielded with technology one to two generations behind state-of-the-art, or their development is delayed for even longer periods as systems are redesigned to include upgrades. This is a particular problem with display technologies, which have greatly accelerated in the last decade. The CRT made wide-spread use of color in the cockpit possible. Flat-panel display technologies in the form of MFDs accelerated this trend by reducing the weight, volume, and power of color displays. The last remnant of older generation indicator displays, the incandescent lamp, is rapidly being replaced by LEDs in push-button designs, which use less power, have greater reliability, and provide tactile feedback (Stratford, 2006; van Wageningen, 2014; Bellamy, 2015).

One solution to the acceleration in lighting and display technologies employed in recent years is to adopt commercial-off-the-shelf (COTS) components and systems (Thomas & Lorimer, 2007). For military aircraft, this solution leverages off avionics developed for the much larger civil aviation community, which can result in reduced costs and shorter lead-times (Wolf, 2016). While there are still concerns about the capability of COTS components to withstand the demanding operational environments of military aircraft, avionics manufacturers have made great strides in designing to and testing against military requirements, even for the harsh conditions in which military rotary-wing aircraft fly. Many recently developed cockpit display systems even provide night vision imaging system (I²) lighting compatibility. However, while considerable attention has been paid to good HFE practices, newer displays tout increased color capability and usage that may in some situations not provide optimal pilot performance. There also is the issue of control over color schemes, as well as consistency across airframes, which may compromise pilot training (see Issue #1 in *New and Continuing Color Issues and Future Research* section). With the possibility of a mixture of displays, there will be great difficulty in knowing which display designs and/or color schemes are the most effective. One solution might

be the application of emerging artificial intelligence (AI) systems in the form of deep learning (artificial neural networks) to analyze and predict which attributes of displays, especially color, produce the best pilot performance.

Artificial intelligence (AI) is the theory and practice of applying computer algorithms to perform complex tasks ordinarily requiring the use of human intelligence. For many tasks involving the interpretation or evaluation of numerical data, AI often can outperform human ability with respect to speed, accuracy, precision, and repeatability. AI applications involving color interpretation have been in use for more than 20 years using traditional AI methods. However, Deep Learning AI methods have been developed recently, and will likely become an important tool for color vision research. Deep Learning also has great potential to provide practical solutions for improving the appearance of color-base applications such as graphic displays when used in challenging operational environments (e.g., the military cockpit). There are a number of potential areas of future AI research that would benefit the use and integration of color in military aviation (see *Future Research* section).

The first of these areas is the optimization of current color displays to allow operators with CVDs to perform just as effectively and accurately as a color-normal operator. Thus, there would be no need to require drone aircraft operators to have color vision requirements equal to those of current on-board aircraft pilots if AI-based software encoding the display could anticipate confusing color usage (or colors difficult to see even for operators with normal color vision) and make reasonable color corrections that eliminate the confusion.

A second avenue of future AI research could involve the standardization of remote control devices to fly or drive semi-autonomous vehicles, particularly in terms of their color graphic display appearance. It would be possible all remote control operators could be trained on a single, universal cross-platform controller device with a color-based interface. The AI software embedded within the controller would use the control settings to issue the corresponding input commands to direct the remote vehicle. Thus, whether the vehicle is a small hand-launched drone, or a full-sized remotely-operated aircraft, the operator would successfully control the vehicle through a simple, color-based graphics display and hand-off the actual mechanics of flying to the embedded AI, and potentially could control multiple vehicles simultaneously.

A third potential use of AI-embedded color-based displays would be to have the display adapt automatically to the needs of the operator in real time, subduing those display elements that are low-risk and irrelevant, while bringing forward and emphasizing the mission-critical information. For example, operating a helicopter in a hover at 50 feet AGL has far different demands for the attention of the pilot than when the aircraft is cruising at an altitude of 2,000 feet. Likewise, flying in degraded visual environment (DVE) conditions may require the use of augmented vision displays rather than physically looking out the cockpit window for visual cues. Arguably, displays need to be better standardized in terms of color usage going forward in the future development of graphic interfaces and glass cockpits. Color-coding (green/amber/red) has been long used to indicate a situation status (e.g., caution and warning) for individual and system parameters, but as systems become more complex, more automated, and combine more information from multiple sensors, there is a need to rethink how to best standardize color displays and to better emphasize the most critical information at any moment in time. AI-based methods may help to guide our reasoning. For example, color information may become more

closely tied to risk management, where the complex nature of risk could be derived through the use of AI methods. Such methods would not only use AI inputs to indicate vehicle status, but could also include information about the attention status of the pilot/operator, as well as the status of other mission-critical resources.

Color in aviation charts and maps.

While some colors have historically and culturally been attached to specific meanings (see *Color in Culture and Symbolism* section), humans appear to have put minimal effort into the development of “consistent and durable” color schemes, a greater emphasis having been placed on aesthetics (Dreyfuss, 1972; Grossman, 1992). The exception to this is in cartography (the science of map making). In this field, a set of conventions have been adopted and historically adhered to. The explanation for this acceptance usually is attributed to the close relationships of commonly depicted features and their natural-occurring colors: blue for water, brown for land and mountains, green for foliage, and white for ice and high (frequently snow-covered) elevations (Robinson, Sale, & Morrison, 1978; Grossman, 1992).

As color is an attribute that can add information (encoding), it is obvious it would find application in maps. While a map has many different elements, color is one of the first of these noticed by users (Campbell & Shin, 2012). This is somewhat due to the intuitive understanding humans appear to have of how colors are used to create an effective and pleasing visual experience. Nevertheless, it is not always clear to the map-maker which colors should be used to best convey the purpose of the map. This is particularly true in aviation applications.

Early pilots used existing paper motorway and railroad maps for navigation. Specialized aviation charts and maps would not come into their own until post World War I (WWI) (Akerman, 2010; Liebenberg, Demhardt, & Vervust, 2016). Two World Wars would cement the necessity of aviation maps. Nearly a century later, technology would make paper maps almost obsolete. The number of colors available would grow from less than 10 to more than 16 million.

Evolution of aeronautical¹⁷⁷ charts and maps.

Before digital map displays, charts/maps used in aviation were (and many still are) printed documents.¹⁷⁸ The first suggestion of creating specialized aerial maps may have been advanced by the German balloonist Hermann Moedebeck in 1888 (Gibbs-Smith, 2013). Frequently referred to as the “father of aviation cartography, he would make annotations on ground-based maps to assist in navigation during his balloon flights.

From the advent of manned flight through the end of WWI, aviators continued to use ground maps (e.g., road and railroad) and hydrographic (river) charts to fly over terrain (Burton, 1953; Akerman, 2010; Lehrer, 2014). The first “true” flight map is usually cited as the first in the series of aeronautical charts developed under the supervision of Moedebeck and published in

¹⁷⁷ An aeronautical chart is a map designed to assist in navigation of aircraft, much as nautical charts do for watercraft and roadmaps do for drivers. The term *chart* generally replaced the term *map* by the mid-1930s. When referring to maps developed to aid in-cockpit navigation, the terms aeronautical, aviation, air, and flight may all be used interchangeably.

¹⁷⁸ While paper has been the primary medium, many maps, dating from as early as 168 BCE in China, were produced on cloth (Doll, 2002). Cloth maps were very prevalent in the military during and after WWII.

1909 by the German Aeronautical Society (Ristow, 1960). The first U.S. government experimental aeronautical charts appeared in the 1920s and were printed in three colors, identifying airfields, occasional navigational aids, topographical features, and prominent landmarks. The advent of WWII created an increased emphasis on accurate and detailed aviation maps, but it was the combination of aerial photography, satellite imagery, and remote sensing technologies of the late 20th century that produce the highly detailed maps used today.

When specialized aviation charts and maps became commonplace in the cockpit in the 1920s, color was a well-established and well-used technique for information presentation. In 1922, both the U.S. Army and Navy began ordering airway charts (known as “strip maps”) of the most often flown routes inland and along coastlines of North and South America (Bors, 1947). These were mostly commercially-produced maps until the National Coast and Geodetic Survey Bureau¹⁷⁹ took over the job in 1927. These maps were printed in 10 colors, from dark green for the lowest elevations, to brown for the highest (very similar to the color scheme still employed today); different colors made the important topographical features stand out (Lehrer, 2014). By the mid-1930s, the entire U.S. had been mapped.

Many of the early charts/maps in the cockpit were printed in a single color of ink, usually black, with grays from halftones. By the 1940s, 7 to 12 colors were common: black was used for projections, names, bridges, etc.; blue for water (e.g., lakes, rivers, canals); yellow for cities; red for aeronautical information (e.g., airways); and up to three greens and five browns for gradients (Bors, 1947). A magenta color was added later to address the readability issues with interior lighting.

An abbreviated visual history of pre-electronic aviation maps used by the U.S. is presented in Figure 114. Represented are: a) a 1920s railroad map typical of those used before the development of specialized aeronautical maps; b) a c1930 U.S. Army Air Corps strip map used to show air routes between various cities; c) a U.S. Army Air Forces 1944 WWII-era cloth chart of Luzon Island, Philippines; d) a U.S. Defense Mapping Agency 1972 Viet Nam-war chart of Ca Mau, Vietnam; e) a 1953 Korean Conflict era U.S. Air Force (USAF) Aeronautical Chart, Japan; f) a 1999 helicopter route chart, New York (National Ocean Service); and g) a current Jeppesen IFR navigation chart...first developed by Elrey Jeppesen¹⁸⁰ in the 1930s and still in use today (Note it uses color to contrast and enhance situation awareness for an approach procedure; after 80 years, it still remains the standard type of map used in most commercial flight operations.).

Most flying at this time was conducted during day-time periods, with more than sufficient illumination to interpret color information. As night-time flight operations began, artificial lighting became necessary to read maps and view instruments (see *Night Combat and the Ascent*

¹⁷⁹ In 1970 a reorganization created the National Oceanic and Atmospheric Administration (NOAA) and the National Ocean Service (NOS) was created as a line office of NOAA. To acknowledge the geodetic portion of NOAA mission, the part of NOS responsible for geodetic functions was named the National Geodetic Survey.

¹⁸⁰ Elrey Jeppesen (1907-1996) was a pilot whose license was signed by Orville Wright. Jeppesen flew a Curtiss JN-4 "Jenny," barnstorming, flight instructing, and performing aerial surveying. During the winter of 1930 and 1931, however, many of Jeppesen's fellow flyers were killed in air accidents, and he attributed their loss to the lack of published flight information. Using a black notebook, he began recording field lengths and notes on lights and various obstacles. He drew airport layouts and included the phone numbers of farmers who could report weather conditions. Soon, pilots asked Jeppesen to share his flight information so often that he began selling copies of his black notebook. Today, Jeppesen remains a respected source for instrument aeronautical charts, GPS navigational data, and flight planning software (Krepelka.com, 2015).

of *Helicopters in Army Aviation* section). Based on research by Burton (1953), Taylor (1985) cites a 1934 U.S. Air Corps Boston to Washington, DC, strip map (printed in red) and a 1935

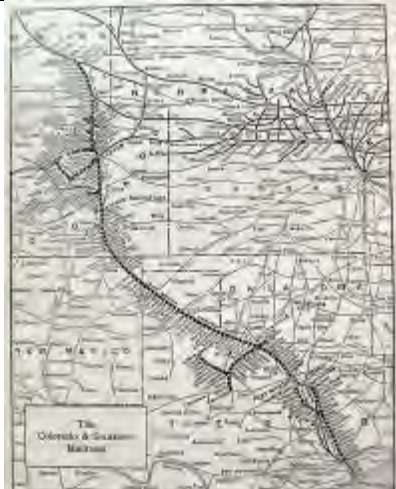
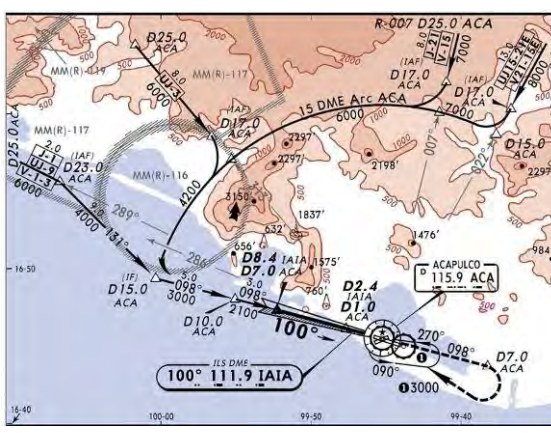
		
a) 1920s railroad map pressed into service	b) c1930 U.S. Army Air Corps strip map	c) 1944 U.S. Army Air Forces cloth chart, Luzon Island
		
d) 1972 Ca Mau, Vietnam (U.S. Defense Mapping Agency)	e) 1953 Korean Conflict era USAF Aeronautical Chart, Japan	
		
f) 1999 New York helicopter chart, (National Ocean Service)	g) Jeppesen IFR navigation chart	

Figure 114. Representative maps depicting the evolution of aviation (aeronautical) maps used by the U.S. prior to modern electronic map displays.

U.S. Coast and Geodetic Survey chart (both experimental) as possibly the first attempts at producing night flying maps and charts.

The need, greatly elevated by WWII, to provide artificial lighting for night flights revealed legibility issues with the inks originally used to produce the colors on many maps and charts. The two major types of cockpit lighting employed in military cockpits were UV and red (see *Crew station lighting* section), and both required changes in the inks used to produce standard colors. Fortunately, both the U.S. Air Corps (with its UV lighting) and the RAF (with its red lighting) had recognized the problem in the 1930s and had investigated alternative printing processes.

With lighting and map legibility addressed, charts and maps became essential cockpit tools, providing more and more information. Today's complex aviation charts and maps contain nearly 150 symbols for cultural and topographical information, as well as 100+ symbols for aeronautical information. They reflect the mosaic of open and restricted airspaces, controlled and uncontrolled airports, and a myriad of features such as Very High Frequency (VHF) Omni Directional Radio Range (VOR) beacons,¹⁸¹ dams, airways, compass roses, and radio antennae. Roads and railroads, which were once the primary navigational aids to pilots, are still depicted.

Current and older maps provide information about terminal areas and airports with their runways and taxiways. The graphic designs manage legibility and attention allocation via mature cartographic methods. Backgrounds are mostly white, with some shading of area data, such as bodies of water, terminal buildings, and runways; area data occasionally are patterned. The saliency of symbols and alphanumerics is manipulated by font size, type style (e.g., boldface, italics), and luminance contrast (NASA Ames Research Center, 2000c).

Consequently, aviation charts have very high data densities, and the presence of color serves as just one of several graphic variables used to achieve the visual hierarchy of the information. Simple charts and maps use chromatic color for grouping, labeling, and “pop-out” of symbols. In more complex charts and maps, color is used for labeling of multiple altitudes of terrain. In the most complicated area and sectional charts, color-labeled symbology is superimposed on multicolored shaded terrain (NASA Ames Research Center, 2000c).

As an example of using color shading, the FAA *Aeronautical Chart User's Guide* describes the colors used to present chart features as two blue tones, one for “Open Water” and one for “Inland Water” (FAA, 2013). In addition, different color tints show bands of elevation relative to sea level. These colors range from light green for the lower elevations, to dark brown for the higher elevations (Figure 115, left), but other tint schemes may be encountered (Figure 115, right).

¹⁸¹ *VHF Omni Directional Radio Range (VOR)* is a type of short-range radio navigation system for aircraft, enabling aircraft with a receiving unit to determine their position and stay on course by receiving radio signals transmitted by a network of fixed ground radio beacons.

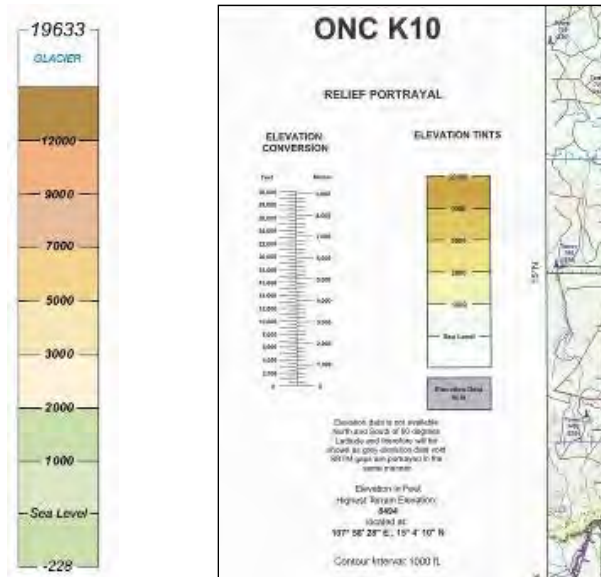


Figure 115. Elevation tints on aeronautical charts: FAA *Aeronautical Chart User's Guide* (left) and National Geospatial-Intelligence Agency (right).

Stepping back briefly from aeronautical maps and looking at the history of using color on maps in general, Taylor (1985)¹⁸² provides an excellent introduction to cartography. He reviews the use of color in maps from ancient times to the present and provides a set of design principles and guidelines for its use in aviation electronic map displays. He points out color is particularly useful in the pictorial presentations very prevalent in early maps, which were hand-drawn and hand-colored.¹⁸³ Beginning as early as the 1500s, color was a highly-used method of presenting continuity in land form (Imhof, 1982). In even the first maps, there is clear evidence that color choice and use was strongly linked to the colors of nature: blue was used for water, green for woodland, red for human settlements, and brown or red for roads (Skelton, 1964). By the late 1700s, color had become standard practice in applied cartography, representing the geographical relationships of many types of scientific data, such as geological, social, economic, meteorological, statistical, and land-use information. As data becomes more detailed, more dimensions for its rendering are required; color provides one such additional dimension (actually three dimensions, hue, saturation, and brightness, as color has three properties). It is worth noting the 1700s presented a confluence of three innovations that strongly influenced cartography (Clarke, 2015, 2017):

- The three-color printing process invented in 1710 by Le Blon (Lilien, 1985);
- The beginnings of statistical theory c1741, with the term “statistik” being first used in 1748 (Hecht, 1987; Friendly & Denis, 2001); and
- The introduction of the concept of a 3D coordinate system (x,y,z) in 1752 by the German mathematician Leonhard Euler (1752).

¹⁸² Taylor's (1985) well-researched and exhaustive narrative of the history and technology of aeronautical map displays prevents any discussion of the subject beyond a summary of his work, at least until the arrival of discrete-element displays in the 1990s.

¹⁸³ The oldest known printed map is Chinese, and was published around 1155. Hand-coloring, and sometimes gold leaf, was used to embellish the original drawing (Taylor, 1985).

Throughout the 1970s and into the 1980s, continuing advancements in display technology transitioned maps from paper to optical projection and then to electronics, first monochrome then color. The first of these advancements was the Projected Map Display Set (PMDS) using maps stored on filmstrips. Filmstrips of reverse format, negative or black maps, were considered, an approach having the supposed advantage of maintaining night dark adaptation while offering high contrast for visibility of important features in bright sunlight (Taylor, 1985). The PMDS consisted of a set of filmstrips and a hardware drive that positioned a filmstrip projected through an optical display system. The display presented a map of the area surrounding a specified geographic location. The PMDS was used in the U.S. Navy's (USN's) A-7 Corsair, which was also the first U.S. combat aircraft to use a HUD (Britton, Parker, & Parnas, 1981; Fighter Aircraft, 2017). Experimental black filmstrip maps also were considered for use in the Combined Radar and Projected Map Display (CRPMD) in the British Tornado strike aircraft in the 1970s. In the CRPMD, return signals from the ground mapping radar were drawn on the CRT screen and overlaid with map imagery from a projected 35-mm filmstrip via a combining mirror. However, the black maps were found to be problematic to pilots used to customary positive-format maps.

The 1970s saw monochromatic electronic displays consisting of multifunction CRTs being offered by the avionics industry as an alternative to projected map displays. While an advancement in display technology, the lacking of color was not considered a step forward in map presentation. Osterhoff, Earl, & McGrath (1966) showed monochromatic copies of maps resulted in decreased low-level navigation performance as compared to the full-colored originals. Early studies of color vs. monochromatic video maps were inconclusive because differences in image quality were considered to be confounded by the presence or absence of color (Williges & North, 1973; Wong & Yaeomnelos, 1973). Taylor (1985) reported strong pilot opposition to the use of non-color map displays in operational military aircraft and monochromatic maps also were rejected for use in helicopter tactical operations with I² devices of the period (i.e., night vision goggles [NVGs] and ANVIS) (see *Night imaging technology in Army aviation* section). Both the U.S. Army and the UK rotary-wing communities developed experimental B/W maps for direct viewing with NVGs (Johnson, 1973). The UK map was produced with symbology designed specifically for NVG viewing (Barnard & Blyth, 1978). Both attempts met with mixed results and were abandoned, mostly due to pilots' strong preference for color. In modern military rotary-wing aircraft, ANVIS have a look-under capability and cockpits provide blue-green ANVIS-compatible lighting that allows adequate discrimination of most map colors. As an aside, many older paper maps designed for red cockpit lighting legibility tend to lose contrast on white paper under ANVIS-compatible lighting due to their use of blue and green inks.

Electronic map displays.

Electronic charts and maps are digital representations of geographic areas, frequently with additional data overlays. In the last decade, they have become ubiquitous, available on computers, phones and tablets, and in automobiles and aircraft (Figure 116). The two types of electronic maps are raster and vector (McMahon, 2017). A raster map can be thought of as an accurate copy of a traditional paper map, providing all the same features. Raster maps offer great reliability, being true color reproductions of official paper versions. Most can be zoomed in and

out, changing the scale; but can appear pixelated when over-zoomed. The information on a raster map cannot be manipulated. CRTs and LCDs can display raster maps.

Vector maps are based on a structured database containing a multitude of data, e.g., city and street names, house numbers, points of interest, traffic flow direction, and road construction. Vector maps contain layers of information providing the user with considerable functionality; the most common of which is navigation. Street maps may be aligned with global positioning system (GPS) satellites, allowing the user's position on the map can be pinpointed

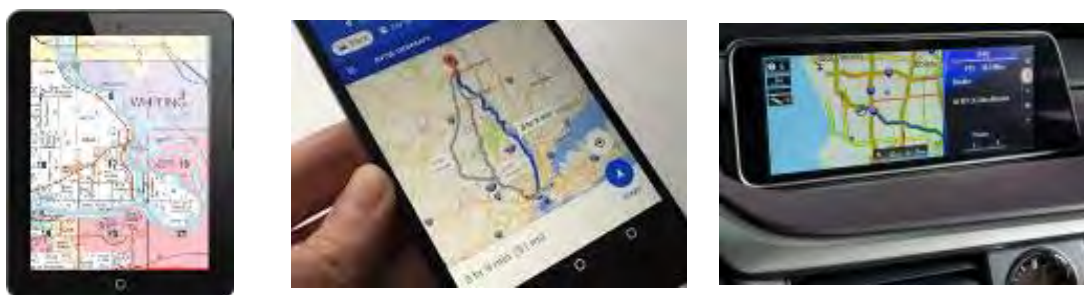


Figure 116. Examples of electronic map devices (Left to right): tablet, phone, and automobile.

and providing directions between two or more points. Vector maps also can connect with information services like restaurant reviews, gas station locators, and weather reports. One major advantage of this type of electronic map is their flexibility to be customized through the use of data filtering or addition. Another advantage is the ability to digitally link the map database with external objects that are dynamic in aspect, e.g., water buoys, and emergency vehicles.

Advances in aircraft and satellite technology have allowed large improvements in the ability and ease of using remote sensing to gather raster geographic information system (GIS) data to be used in electronic maps.

Early guidelines for map design mostly addressed purpose and esthetic appearance. These are still necessary characteristics for cockpit maps (paper or electronic), but functionality, specifically regarding symbol coding and legibility, of which color is a major attribute, is of greater importance. In the last few decades, principles of cognitive psychology have played a large role in the design of map and map displays. Cognitive psychology encompasses perception, learning, memory, language, reasoning, and thinking (cognition). Good HFE principles involve applying this body of knowledge of how people process information to the design of systems to make them easier to use efficiently and safely (Clay, 1993). Nowhere is this more important than in military rotary-wing flight (Harwood, 1989), where pilots must make rapid and timely decisions while flying at airspeeds approaching 150 knots (173 miles per hour/278 kilometers per hour) at heights of 25 feet (7.6 meters) or less above trees or vegetation.¹⁸⁴

¹⁸⁴ For U.S. Army flight operations, the following terrain flight modes are defined: (1) Nap-of-the-Earth (NOE) – Flight is conducted at varying airspeeds as close to the earth's surface as vegetation and obstacles permit up to 25 feet above trees and vegetation in the flight path; (2) Contour Flight – Flight is conducted at low altitudes conforming to the earth's contours. It is characterized by relatively constant airspeeds and varying altitude as dictated by terrain and obstacles. Contour flight is further defined as operating with the skids or wheels between 25 and 80 feet above highest obstacle (AHO), and; (3) Low-Level Flight – Flight at a constant altitude and airspeed, dictated by threat avoidance. Low-level flight is further defined as operating with the skids or wheels between 80 and 200 feet AHO. (Department of the Army, 2012)

Today's electronic map displays are some of the most visually complex information displays in the cockpit (Widdel & Post, 1992). Some of this complexity is due to the high data density (Tullis, 1987); another cause is the use of color coding. Most map display designs still adhere to traditional cartographic rules and conventions. But, the operational tasks of today's map displays differ from those for historical map presentations, and traditional approaches, including usage of color, may not be applicable to some designs. Unnecessary visual clutter may result from color over usage, especially when color serves no specific purpose (Hopkin & Taylor, 1979; De Ree, 1990).

In electronic map displays, it's the software design providing the mapping information that requires the most attention. Electronic map developers have adopted a "top down" approach to composing the map text, symbols, graphics, and background elements in the display format. The goal being a hierarchy of structures perceived as corresponding to the function and importance of the information to the user. This approach is believed to provide the map with clarity, order, and meaning, increasing the efficiency of communication transfer (Wood, 1968; Dent, 1972).

While the first use of color CRTs in the cockpit was demonstrated to the USAF in the 1970s (Patzner, 1996), the shadow mask CRT was still the only feasible option for electronic charts and maps into the late 1980s (Kaufmann & Glavin, 1990). In the shadow-mask design, one-third of the mask is dedicated to each primary color (red, green and blue). The result is a shadow mask CRT produces less than one-third the luminance of a monochrome display. The implication is the luminance range for color monitors is not as great as for monochrome displays. CRT-presented map displays for the most part were scanned aeronautical charts, often illegible (Lohrenz, Myrick, Trenchard, Ruffner, & Cohan, 2000).

Hale and Billmeyer (1988) conducted a literature review of studies investigating the advantages and disadvantages of employing color CRTs in the cockpit both as primary displays and map displays. While color CRTs already had seen limited fielding in commercial (e.g., Boeing 757, 767, and Airbus A310) and military (e.g., F-14 Tomcat, A-7 Corsair, F-18 Hornet, E-6A Mercury, P-3 Orion, F-15 Eagle, and the Tornado) aircraft, opinion was still divided as to how effective this technology was in assisting pilots in information processing.

Their overall conclusion was "with the advancement of color display technology and with proper design and application, the use of color on aircraft CRTs will prove beneficial. In addition to general pilot acceptance, color CRTs provide the capability of improving symbol definition, allowing for the presentation of more information on the (display). Colored mapping displays have significantly reduced pilot workload and are probably the most efficient utilization of color CRT (technology)."

More specifically, Hale and Billmeyer (1988) cite the following advantages and disadvantages of color CRT use, which are equally applicable to the AMLCD color technology that has almost totally replaced them:

Advantages

- Search time can be reduced by 70% when using color (Krebs, Wolf, & Sandvig, 1978; Luder & Barber, 1984); this is attributed to the belief shape coding is processed in a relatively slow, serial manner, whereas color coding is processed in a faster, parallel manner.
- Color substantially reduced workload in extracting information from the display (Witt & Strongman, 1983); this is attributed to the reduced search time.
- Pilots express an extensive preference for color displays (Aretz & Calhoun, 1982; Reising & Calhoun, 1982); reasons given were mainly decreased search time and improved legibility of mapping displays.
- Color appears to be a scheme by which a need for more complex and dynamic displays can be met (Reising & Calhoun, 1982).
- Full color is essential for map displays (McGlade & Jordan, 1984); usefulness of color coding in displays tends to increase with information density and complexity, and maps are considered to be the most complex form of information displays.
- Color provides for increased symbol visibility and detectability (Krebs, Wolf, & Sandvig, 1978).
- There is a reduction in errors with color symbols vs. achromatic symbols (Wagner, 1984).

Disadvantages

- The availability of color can illicit its overuse; too many colors can be detrimental, especially when they are similar; similarly, too many irrelevant colors in a display can become "noise" (Krebs, Wolf, & Sandvig, 1978).
- Color CRTs require more power, produce more heat, and have reduced vibration tolerance (Banbury, 1984); this color-related disadvantage disappears with the arrival of solid-state technology and the AMLCD.
- Misconvergence of the primary colors is present in shadow mask CRTs; subjective image quality of a color display degrades significantly as misconvergence increases above approximately 25% of spot width (Robertson & Jones, 1984).
- There are a number of perceptual phenomena (e.g., color stereoscopy, chromatic induction, McCollough effect)¹⁸⁵ that can interfere with normal, predicted perception of colors (Walraven, 1984); these phenomena are difficult to predict and may lead to pilot errors.
- Color wash out is possible in the presence of high ambient illumination on the display (Boot, 1984).
- A known proportion of the general population can have difficulty with specific colors; 8% of the U.S. male population¹⁸⁶ and 0.4% of the U.S. female population has a red-green deficiency (dichromatism) (Narborough-Hall, 1985). This issue is mitigated somewhat by visual standards applied to aviation candidates (see *Color Vision Tests and Standards* section).

¹⁸⁵ *Color stereoscopy* is a visual effect where color of an object has an influence on its apparent distance in binocular perception. Chromatic induction is the modification of the visual response that occurs when two color stimuli (of any spectral irradiance distribution) are viewed side-by-side in which each stimulus alters the appearance of the other. The McCollough effect is a phenomenon of human visual perception in which colorless gratings appear colored contingent on the orientation of the gratings.

¹⁸⁶ 8% is usually cited for males of north European ancestry; 3-4% for males of African ancestry; and 3% for males of Asian ancestry (Pacheco-Cutilla, Edgar, & Sahraie, 1999).

While not distinct disadvantages, Hale and Billmeyer (1988) caution the use of color in cockpit design (especially color selection) is subject to possible designer and user inclinations towards aesthetics over validated performance data (Martin, 1984; Tufte, 2001; Stone, 2006).

In the late 1990s, the full-color AMLCD became the preferred technology for aviation map displays (Snow, Jackson, Meyer, Reising, & Hopper, 1999). This discrete-element display technology was a perfect match for digital maps (digital cartography).¹⁸⁷ Electronic map displays, used primarily for navigation, are the combination of computer, digital imaging, GIS, and GPS technologies (United Nations, 2000). While not without disadvantages, digital cartography offers the advantages of simplicity of continuous and rapid updating, easy conversion of map projections, ease of storage and retrieval, and seamless integration capability for overlaying of additional information. However, typically color layers are electronically draped over one another by selectively controlling the appearance of pixels or color features. This technique can create a view of the region for the user similar to a satellite image of the area, a paper chart, or slope-shaded terrain relief. While such presentation techniques can be useful in aiding the user to visualize important features of a particular area, performing the necessary calculations and transferring the patterns to image memory are time consuming operations. Consequently, a user can sometimes be required to wait a considerable period of time while the data are calculated and displayed. Wiant (2003) has proposed one method for mitigating this problem. The method can be applied to each color fragment in a map scene, defining the color fragment characteristic component value based on a location characteristic associated with a location on the map, setting a test value, and then comparing the color fragment characteristic component value to the test value to determine whether the color fragment should be displayed in an overlay color.

Another, and more relevant, advantage is the ability to easily add color schemes. AMLCDs provide these capabilities as well as improvements over CRTs in luminance, luminance uniformity, dimmability, resolution uniformity, immunity to ambient illumination washout and color de-saturation, night vision imaging system (e.g., ANVIS) lighting compatibility, and increased usable display area to panel area ratio (Rupp, 1986; Tannas, 1994).

Color selection and design guidelines.

The ability of today's military to define a color selection for electronic charts and maps has been severely reduced. As with cockpit lighting and other display avionics, adopting or at least leveraging off of COTS components and systems has become the only cost-effective approach. New generations of commercial mapping hardware and software come so rapidly, a dedicated military development program is not practical. However, military programs can and should still base acquisition decisions on known application requirements (which can be unique for military applications), user experience and preference, and recommendations of HF, color science, and cognitive science subject matter experts.

Kaufmann & Glavin (1990) developed a testbed for designing and using electronic charts as navigational aids for mariners. Their experience produced a number of conclusions and recommendations regarding color selection, coding convention, and design in map displays.

¹⁸⁷ *Digital cartography* is the process by which data is compiled and formatted into a virtual image.

These are directly applicable to similar aviation map displays. Most of the recommendations are in general agreement with guidelines developed by other researchers for generalized display applications.

For color selection:

- Colors must be well defined by a recognized color system (e.g., 1931 CIE), not by just a color name.
- As the difference between the dominant wavelengths of two colors increases, the ability to discriminate between those colors also increases. (Silverstein & Merrifield, 1981)
- The number of colors required for an effective color coding strategy is closely related to color selection. Color discrimination is strongly affected by the number of colors used.
- The total number of colors used should be kept at a minimum with careful consideration given to the priority of color-coded information.
- For operational color displays, a selection of three to four colors is recommended if absolute color judgements are required. Six or seven colors can be used, with a maximum of ten when applications require comparative discrimination.
- The optimal number of colors depends on the visual task. An absolute color discrimination task involves the recognition and identification of colors. A comparative color discrimination task requires the comparison of simultaneously displayed colors. The number of discriminable colors and the accuracy of color selection is much greater for comparative judgements than for absolute judgements. (Silverstein & Merrifield, 1985)
- As the number of colors used increases, so does the probability of confusion between colors, the time required to detect any specific color, and the demands on the hardware for reliably reproducing each color.

For color coding convention (generalized, but most applicable to hydrographic charts):

- Blue for water, depth shades, and contours
- Green for intertidal foreshore, drying areas
- Yellow and tan for land areas
- Brown for topographical contours and built-up areas
- Red, magenta for navigational aids, routes, limit lines, and important information
- Black for text, buoys, line features

For color display design:

- High ambient illumination desaturates colors and reduces discriminability. It is recommended direct sunlight be filtered, or map displays be shielded.
- Low luminance levels can cause colors to be less discriminable. Some colors may disappear if luminance levels are too low (e.g., during night flight).
- Luminance uniformity across the display should not differ by more than 20% for any of the colors presented on the display.
- Color perception is enhanced when symbols are displayed on a light background rather than a black background. However, a light background should not be overly bright;

and in some cases, a dark background may be more appropriate, e.g., for night viewing when dark adaptation must be maintained. (Silverstein & Merrifield, 1985)

- The relative brightness of specific colors should be adjusted according to task demands. Colors that are too bright can be distracting.
- Color-coded symbols should subtend more than 15 minutes of visual arc, and preferably 45 minutes of arc.
- Redundant coding should be implemented for small, important symbols.
- As the number of colors used for coding increases past an optimal amount, both error rate and reaction time increase. The number of recommended colors ranges between four and ten.
- Colors should have the same meaning across multiple displays. Coding in an unconventional scheme or using unusual colors may cause interference by emphasizing unnecessary features. A survey of potential users should be conducted to identify the most widely accepted color use scheme.
- Pure (saturated) blue should be avoided for alphanumeric and small symbols (Tullis, 1987).
- Borders between color areas should have both color and brightness (luminance) contrast to enhance color discrimination (Wolf, 1983).

While less of a problem in the military pilot community, Kaufmann & Glavin (1990) emphasize the need to address potential visual performance issues of the target user population for a given map display design (including color scheme). The population should be screened for color vision deficiencies (CVDs). When older or unscreened users are expected to be a significant portion of the user population, special design options should be considered. These include: the use of colors that contain a mixture of all three primary colors; avoiding small symbol sizes; using luminance differences between colors; and using redundant coding methods.

Many of the above recommendations can be found in the numerous guidelines produced by the aviation community, and these are largely in agreement with recommendations for color displays in general (see *Guidelines for Use of Color in Cockpit Displays* section). FAA (2014) AC 120-76C, Electronic Flight Displays, contains a number of statements addressing color and map display presentations (e.g., terrain navigation and weather radar). These can be summarized as:

- While symbology should be coded in more than dimensions, color alone for coding information has been shown to be acceptable in some cases, such as weather radar and terrain depiction on the lateral view of the navigation display.
- The consistent use and standardization of color is highly desirable. In order to avoid confusion or interpretation errors, there should not be a change in how colors are perceived over all expected conditions. Colors used for one purpose in one information set should not be used for an incompatible purpose that could create confusion or misinterpretation in another information set.
- Graphic depictions such as terrain maps and synthetic vision presentations may use more than six colors and color blending techniques to represent colors in the outside world or to emphasize terrain features. These displays often are presented as background imagery, and

the colors used in the displays should not interfere with the flight crew interpretation of overlaid information parameters.

- Dynamic information should not appreciably change shape or color as it moves. Objects that change size (e.g., as the map range changes) should not cause confusion as to their meaning and should remain consistent throughout their size range.
- Displays or layers of displays with uniformly filled areas conveying information such as weather radar imagery should be independently adjustable in luminance from overlaid symbology. The range of luminance control should allow detection of color differences between adjacent small filled areas no larger than 5 milliradians.

Weather radar is of great importance in modern aviation. It is used to locate areas where rain and snow are present. Color schemes are used to present the intensity of these precipitations. While color schemes can vary, the most common scheme is:

- Light green – light rain, or light rain aloft not reaching ground
- Dark green – light to moderate rain
- Yellow – moderate rain
- Orange – heavy rain
- Red – very heavy rain or rain and hail
- White or blue – snow
- Pink – freezing rain or sleet or mix of winter precipitation types

Representative weather radar images are presented in Figure 117.

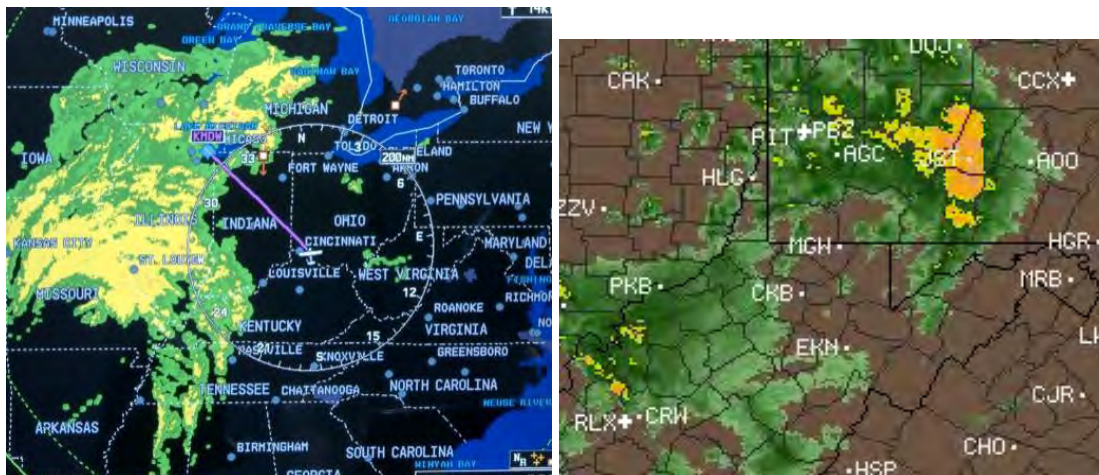


Figure 117. Examples of weather radar imagery.

A number of moving maps are adding an overlay of IR satellite weather data, a type of infrared imagery known as water vapor imagery (Conway, 1997). In this new color satellite image, purple and darker shades of blue are indicative of cloud tops at high altitudes. At the other end of the spectrum, shades of red and orange are indicative of shallow clouds with tops near the earth's surface.

The four-color mapping problem.

There is an interesting historical note regarding the issue of the optimal number of colors needed or recommended for use in planar (2D) maps (and map displays). It is referred to as the four-color mapping problem (Francis, Bias, & Shive, 2010). In 1852, Francis Guthrie, a student at University College London, noticed that four colors were sufficient to color a map of the counties of England with no neighboring counties having the same color (Appel & Haken, 1989; Wilson, 2004). While a number of proofs of this property were posed over the ensuing decades were considered inadequate, it was not until 1977 that an accepted mathematical proof of the four-color theorem was presented (Appel, Haken, & Koch, 1977). However, both before and after this achievement, the four-color mapping problem rarely affected the actual coloring of maps, with maps frequently having more than four colors due to other constraints and requirements.

The importance of the theorem does not lie in its direct utility but rather in its having been a motivating influence on coloring and inductive techniques in map theory (Amit, 2013). Frequently, map designers select colors that will promote rapid and efficient searches for required information (Christner & Ray, 1961; Phillips, 1979). Francis, Bias, & Shive (2010) have suggested “searches for such color designs could be simplified if the number of colors actually applied to a map were first specified – say, to be the mathematically favored number four.” They refer to this as the psychological four-color mapping problem. To investigate a solution to this problem, they designed a model of visual search and demonstrated how to apply it to the task of identifying the optimal colors for a map. Using a set of 7 colors for a visual search experiment in which participants were asked to locate a target region on a small map, they used the model to predict search times and identify the color assignments that *minimized* and *maximized* average search times. The differences between these search times across the two model-generated map designs were demonstrated to be substantial. The model then was tested with a larger set of 31 colors on a map of English counties (a replication of the Guthrie problem) under conditions in which participants might memorize some aspects of the map. Empirical tests of the model showed the model’s best colored version of this map was searched 15% faster than the correspondingly worst colored map. Thus, the color assignment seemed to affect search times in a way predicted by the model, and this effect persisted even when participants used other sources of knowledge about target location. For a given map design, the model computes the average search time across all regions for every possible color combination. The color combination that produces the shortest average search time is the optimal coloring for that map design. Unfortunately, aviation electronic maps usually have a predefined color selection.

Hardware issues.

While cognitive issues of color electronic map displays are extremely important, it is necessary to return to the hardware issues of color map displays, i.e., the display itself. Disregarding the issues of poor handling and storage of hardcopy (printed) maps, such maps have stringent color reproduction quality control. Softcopy maps (e.g., maps produced on electronic displays) are subject to considerable variations in color reproduction due to presentations on devices of differing color gamuts and color-mapping schemes (Langran, 1984). In addition, consideration must be made for the differences in the use of subtractive color for

hardcopy maps and additive color for CRT and AMLCD map displays (see *Color Science* section). This problem suggests different color constraints be placed on hardcopy and electronic (softcopy) designs. Indeed, color is a complex piece of the cartographic design and is, not surprisingly, the most frequently criticized aspect of electronic map displays (Monmonier, 1996; Campbell & Shin, 2012).

User requirements.

User requirements for aeronautical charts are more precisely defined than for other applications (Langran, 1984). In comparison, aeronautical charts also are more cluttered and of higher information density. Information includes navigation data, location and shape of land features (e.g., major roads, rivers, railroad routes, and coastlines), and natural and manmade landmarks (e.g., mountains, plateaus, forests, monuments, buildings, and airports). As flight altitude increases, navigation information increases in importance over terrain and landmark information (Langran, 1984).

For U.S. Army helicopters flying nap-of-the-earth (NOE),¹⁸⁸ paper charts at a scale of 1:50,000 have been typical. But, for a typical mission, the volume of paper maps required can be bulky and difficult to manage in a confined cockpit when attention must be divided between in the cockpit reading maps and out of the cockpit flying. NOE flight requires information be acquired quickly by glancing at a map, which therefore must emphasize vertical features and relief. Slope is especially important for NOE flight. The limited field-of-view and oblique perspective from flying close to the ground cause features to appear strikingly different from the traditional bird's-eye view; a scale of 1:100,000 has been suggested for low altitude flights (Langran, 1984).

When rapid acquisition of map features is required, color can serve an important role. The shape of drainage and coastlines has been agreed upon by pilots as being among the most useful map features for orientation. However, blue used to outline lakes and coasts provides minimal visual acuity. The majority of hydrographic features should be outlined in black. Those not outlined in black should be shown in solid blue. Man-made features on coastlines, such as seawalls and dams, also should be shown with a heavy black line.

In the design of aeronautical charts, modern cartographers should draw heavily from the well-researched physiological, perceptual, and HF principles of vision science, while still being aware of well-ingrained methods of map design.

Moving map displays.

The progression of electronic maps from static to dynamic presentations (i.e., moving maps) was an obvious one, capitalizing on advancement in computer processing and GPS technologies. The idea behind an aviation moving map is a simple one. It's a representation of an aircraft's position on a geographic area. As the aircraft's position changes, so does the map area, updating itself to keep track of the aircraft's progress. For pilots, this greatly increases situation

¹⁸⁸ *Nap-of-the-earth* (NOE) is a flight profile of varying airspeed and altitude usually performed below 25 feet above ground level (AGL) and below 40 knots airspeed.

awareness (Matarozza, 2005). In addition to allowing the pilot to see his aircraft's position on a map section, moving maps can show positions of other aircraft, as well as topographical features and weather conditions. When properly designed, moving map displays can present information more efficiently than paper maps such that pilots can obtain all the information required to assess a situation and accomplish a task with a quick glance (Ruffner, Lohrenz, & Trenchard, 2000). These systems also should provide pilots with the ability to actively select/deselect displayed information (Rogers & Spiker, 1988; Unger & Schopper, 1995).

One of the most important advantages of the modern moving map is its ability to reorient itself with respect to aircraft flight direction, an important cognitive advantage for the pilot, who no longer has to mentally adjust map-aircraft orientation. (Evans & Pezdek, 1980; Hintzman, O'Dell, & Arndt, 1981; Aretz, 1989; Harwood, 1989).

The major hardware requirements for a moving map display beyond those of a static map display have blurred with recent advances in computer hardware and software. But, for the first generations of modern moving map displays (c1990s), system requirements included (Craven, 1991):

- The ability to rapidly move regions of the display, so as to facilitate generation of the moving map;
- An overlay mechanism, ensuring a change in aircraft situation or other selections does not require complete regeneration of the map image; and
- Low level support to rapidly fill (color in) areas of terrain (e.g., water, forest, etc.)

The concept of a moving map in the cockpit is decades old (at least c1949), although on a somewhat limited basis. One of the earliest was an ad hoc application of the Decca Navigator System, a hyperbolic radio navigation system used in WWII by Royal Navy ships (Blanchard, 2015). The display, known as the Decca Flight Plotter, used rolls of film displaying simple route graphs. A major problem with this system was it was based on speeds associated with ships and not on the much greater speeds at which aircraft traveled. In the 1950s, rolls of paper maps came into use; these continued into the 1960s. It would be the arrival of computer imagery and data storage technology in the 1980s that would provide the basis for today's moving map displays.

In the late 1970s, Baty (1976) evaluated one of the earliest uses of CRTs as a moving map. He conducted a simulator experiment designed to study the advantages and disadvantages of incorporating a simple horizontal flight-path predictor on electronic CRT map displays. These early moving maps generally were monochromatic. But, modern AMLCD moving maps are full-color. Today's commercial aviation devices usually allow two basic color options. In one device, when the Background Color ON option is selected, the display presents an olive green background color for the map; this creates a neutral background for displaying all of the text and map features. The Background Color OFF option presents a black background for the map, which pilots may prefer for flying at night. There usually is an option to select the display of Meteorological Terminal Aviation Routine Weather Report (METAR)¹⁸⁹ airport color coding. This setting colors the airport symbols of airports with METAR reports according to visual flight

¹⁸⁹ METAR is a format for reporting weather information. A typical METAR contains temperature, dew point, wind direction and speed, precipitation, cloud cover and heights, visibility, and barometric pressure data.

rules (VFR), instrument flight rules (IFR) and Marginal VFR flight conditions. Most all commercial devices provide the capability to turn on/off topography color shading.

Today, moving map technology is part of an electronic flight bag (EFB),¹⁹⁰ an information display that duplicates all of the paper information a pilot used to carry around in an actual canvas bag (e.g., flight manuals and navigation charts). For the civil aviation private pilot, a full navigation map took kit can be packaged into a handheld (or surface-mounted) GPS capable device with a 7-inch display. FAA charts, flight planning capability, detailed airport information, weather, and traffic data are available at the push of a button. Wi-Fi connectivity allows real time updating.

A number of studies have investigated the effect of color (in conjunction with other coding methods) in moving maps. However, in many of these studies, the color schemes and tasks were limited, making it difficult to extend conclusions to broader, more general applications. In one study investigating pilot preferences with vector moving map displays, height-above-terrain was presented as a two-color shaded overlay to a base map, where yellow denoted terrain elevations at the aircraft altitude ± 16 meters, and red denoted all higher terrain elevations (Lohrenz, Trenchard, Myrick, Zuyle, & Fechtig, 1997). This color scheme was intended to reduce pilot workload in interpreting contours and shaded elevations (as compared to B/W imagery). Most subject pilots responded favorably to the two-color scheme; 87% judged two colors (as opposed to one or many) to be appropriate. However, fewer subjects approved of the choice of colors (yellow and red), which had been selected for their strong association with “warning” and “danger,” respectively. Several subjects voiced concern over the use of red when flying with NVGs. The researchers stated that in study debriefings almost every subject had an opinion regarding the use of color (mostly the color selection). As a result, it was strongly recommended the color(s) of any new overlay be considered carefully to ensure that it will be clearly visible against the existing map background and any competing overlays. The researchers noted these recommendations are supported by numerous other studies conducted to identify optimum color combinations for map displays (e.g. Rogers & Spiker, 1987; Merwin & Wickens, 1993; Nordwall, 1999). One important recommendation from all of these studies was “the appropriate use of color can effectively alert pilots to important map features (e.g. threats or terrain obstructions), whereas poorly chosen colors can obscure features and cause the map to be confusing and ineffective (Nordwall, 1999).

In a white paper looking at the use of color on airport moving maps and cockpit displays of traffic information (CDTIs), Gabree, Chase, & Cardosi (2014) concur with the basic premise confirmed early in the development history of color displays by Christ (1975) and others “that color can be an effective method for coding visual information, making it easier to locate and identify symbols on a display.” They also repeat the caution careful consideration should be given in the use of color, as excessive or inappropriate use of color can add confusion to a display (Chamberlain, Heers, Mejdal, Delnegro, & Beringer, 2013). In their paper, they attempt to review the expansive volume of color use guidance in electronic displays, pointing out that it is spread across FAA regulatory and guidance material, HF technical reports, and papers from many different fields of color science. Additionally, they note much of this information is not

¹⁹⁰ The electronic flight bag (EFB) is named after the traditional flight bag used by pilots to carry paper maps and charts. The EFB is an electronic information management device. FAA Advisory Circular (AC) No. 120-76C (2014) defines an EFB as an electronic display system intended primarily for cockpit/flight deck or cabin use.

presented in a way that clearly specifies how it can be applied to avionics displays. In their summary, a number of HF issues are identified for color use on airport moving map displays and CDTIs:

- Use of red, amber, and yellow: Overuse or inappropriate use
 - The use of the colors red and amber/yellow are to be reserved for warnings and cautions, respectively. However, these colors are sometimes considered for use on airport moving map displays in non-alert situations so that the color of the information on the display is identical to what the pilot would see out the window. The overuse of these colors (or colors that are confusable with these colors) in non-alerting situations may desensitize the crew to the urgency of alerts or distract the crew with a perceived alert where none is intended.
- Use of blue: Difficulty seeing blue in certain settings
 - Pure blue should not be used for important information because it has low luminance on many display technologies. Pure blue should not be used for the display of small, detailed symbols.¹⁹¹ Red and blue should not be presented adjacent to each other more than momentarily.
- Consistency of colors: Lack of consistency with colors on other flight deck displays
 - Avionics displays on the flight deck should conform to the same color coding philosophy (scheme), i.e., colors that are assigned a meaning should be used consistently across all displays. For example, if there are two displays showing traffic information, the pilot could be confused if one display differentiates between airborne and ground traffic with a color change, but another display does not. Using conventional color coding schemes in the aviation community will help to keep color coding relatively consistent, and the addition of a new display into the flight deck is less likely to conflict with existing color schemes.
- Redundant use of color: Lack of redundant coding
 - Color is an enhancement for understanding the display information leading to performance improvement, but it should not be the sole means of discrimination of critical information. Color-coded information should be accompanied by another distinguishing characteristic such as shape, location, or text.
- Color discriminability: Traffic is not always easy to see
 - Avoid using many different colors to convey meaning on displays.
 - Each coded color should have sufficient chrominance separation so it is identifiable and distinguishable in all foreseeable lighting and operating conditions and when used with other colors. Colors should be identifiable and distinguishable across the range of information element size, shape, and movement. The colors available for coding on an electronic display system should be carefully selected to maximize their chrominance separation. Color combinations similar in luminance should be avoided (for example, navy blue on black or yellow on white).

¹⁹¹ Unfortunately, some moving maps use dashed blue lines to outline Restricted Areas, making them difficult to see in sunlight.

- When a background color is used (e.g., an achromatic gray), it should not impair the use of the overlaid information elements. Labels, display-based controls, menus, symbols, and graphics should all remain identifiable and distinguishable. The use of background color should conform to the overall flight deck philosophies for color usage and information management.
- If texturing is used to create a background, it should not result in loss of readability of the symbols overlaid on it, nor should it increase visual clutter or pilot information access time. Transparency is a means of seeing a background information element through a foreground one – the use of transparency should be minimized because it may increase pilot interpretation time or errors.
- Afterimages: Potential for afterimages following color removal (disappearance)
 - An afterimage is an illusory perception of a color persisting after the removal of that color from the display (Wade, 2000). Afterimages are created in the retina of the eye and are particularly noticeable when a bright color is removed after focusing on it. The color of the afterimage appears as the perceptual opposite of the color which was previously on the display; e.g., the removal of a green stimulus (such as when transitioning from ANVIS/NVGs or a green HUD will result in a red or magenta afterimage; the removal of a red stimulus will result in a green afterimage; and the removal of a blue stimulus will result in a yellow afterimage. For example, if an airport moving map uses a blue outline to highlight a runway when it is in use, its sudden disappearance may cause the flight crew to perceive a yellow afterimage (a yellow outline surrounding the runway). Afterimages will move as the eye moves, so if the pilot shifts gaze away from the display the afterimage will no longer appear in the same location. Afterimages can be vivid (and therefore distracting) if the display is bright or if the pilot spends a significant amount of time focusing on the display.
- Display brightness: Appropriate brightness for ambient lighting conditions
 - Colors should track brightness so chrominance and relative chrominance separation are maintained as much as possible during day-night operations.
 - Luminance and color differences should not be confusing or ambiguous under any operating ambient illumination conditions. The specific colors should be consistent with change in brightness on the displays over the full range of ambient light conditions.
 - Each coded color should have sufficient chrominance separation so it is identifiable and distinguishable in all foreseeable lighting and operating conditions and when used with other colors. Colors should be identifiable and distinguishable across the range of information element size, shape, and movement. The colors available for coding on an electronic display system should be carefully selected to maximize their chrominance separations.
 - Requiring the flight crew to discriminate between shades of the same color for distinct meanings is not recommended.
 - Adjacent colors should not be equal in luminance when discrimination of edges or detail is important.

Unequivocally, the operational requirements of a moving map system stated by Craven (1991) have been met and surpassed by the electronic hardware and software advancements of the recent decade. However, a number of HF and cognitive issues frequently arise in these state-of-the-art displays. One such problem is that of terrain coloring and its impact on situation awareness, as suggested by McCauley & Gannon (2005):

...a significant drawback of earlier terrain situation awareness (map) display systems is they provide detailed terrain elevation information only for terrain elevations above a pre-selected 'comfort zone.' Except for color coding large bodies of water and certain non-dynamic information (e.g., restricted air space, airport locations) on the display, these earlier systems eliminate terrain details below the elevation of the pre-selected 'comfort zone.' Consequently, these earlier terrain situation awareness display systems were limited to the display of tactical information to which a pilot reacts in the short term.

(The) limitations of the earlier systems have been overcome by a method developed by Feyereisen & Misiak (2004) for dynamically displaying terrain situation awareness information. In their method, an integrated display apparatus dynamically displays terrain situation awareness information over a selected distance relative to an aircraft's current position and altitude. The apparatus displays a color-coded representation of a strategic portion of the terrain elevation data having an elevation less than a pre-selected strategic altitude threshold determined relative to and less than the current altitude data. The color-coded representation of strategic terrain elevation data includes a monochromatic scale graduated as a function of terrain elevation relative to mean sea level. The apparatus also displays a color-coded representation of a tactical portion of the terrain elevation data having an elevation greater than the pre-selected strategic altitude threshold. The color-coded representation of a tactical portion of the terrain elevation data includes color coding as a function of terrain elevation relative to the altitude above ground data. As such, different colors are used to represent different tactical portions of the terrain elevation data. For example, one color (e.g., green) represents a safe portion of the tactical terrain elevation data having an elevation between the strategic altitude threshold and a pre-selected caution elevation below the altitude above ground data; a second color (e.g., yellow) represents a caution portion of the tactical terrain elevation data having an elevation between the caution elevation and the altitude above ground data; and a third color (e.g., red) represents a warning portion of the tactical terrain elevation data having an elevation greater than the altitude above ground data.

Existing aircraft display systems are capable of simultaneously displaying different color sets (e.g., safe/caution/warning) for absolute (relative to mean sea level) terrain elevation data and aircraft-relative terrain elevation data. For example, the color set displayed for absolute terrain elevation data is typically green-tan-brown, and the safe/caution/warning color set displayed for aircraft-relative terrain elevation data is typically green-yellow-red. However, a significant problem that arises with the simultaneous display of different color sets for absolute and aircraft-relative terrain elevation data is pilots often become confused by the different color sets used, and in particular, by the similar colors used especially in the green and yellow-tan terrain elevation data color bands. Therefore, it

would be advantageous to have a system and method capable of eliminating color confusion between absolute terrain and relative terrain in aircraft displays.

A solution proposed by McCauley & Gannon (2005) to the potential terrain color confusion problem is a system having a database for storing terrain data, a processing unit, an altitude determination unit, and a visual display. As (an) aircraft proceeds along a flight path, the processing unit determines the aircraft's current position and compares associated terrain elevation data stored in the database with aircraft altitude data received from the altitude determination unit. For this example embodiment, if the processing unit's comparison of the stored terrain data and altitude data indicates relative terrain data need not be displayed, then the processing unit provides absolute terrain color renderings to the display. However, if the processing unit's comparison of the stored terrain data and altitude data indicates relative terrain data should be displayed, then the processing unit removes the hue from the absolute terrain color renderings on the display and replaces the color, for example, with a grayscale. Therefore, by removing color from an absolute terrain layer if relative terrain color information is displayed, the system eliminates terrain color confusion between the absolute and relative terrain data shown on the display.

Electronic map displays in U.S. Army cockpits.

Moving map displays, consisting of full-color AMLCDs, are utilized in all modern U.S. Army aircraft. They are depicted in Figure 118. While structural layout and nomenclature differences exist across aircraft, the basic principles of operation and the use of color share enough similarities to make it instructive to look at one Digital mapping System (DMS) in some detail, i.e., in the UH-60M Blackhawk.

The DMS in the UH-60M usually displays maps on one of the two center MFDs (see *UH-60M Blackhawk crew station* section). The digital map accepts mission-relevant map data loaded into the system through the Data Transfer System (DTS).¹⁹² These maps are presented as an underlay on the navigation display (ND) or the tactical map (TAC MAP) display.

Mission-related map displays are presented in two primary sub-modes: digital moving map and static map. The digital moving map includes the controls for the presentation of data in different selectable formats: display orientation (heading-up, track-up, North-up), decentering/panning, chart scales, magnification, and flight plan overlay.

The ND display is in the form of a chart map in a heading-up orientation with the helicopter position at the center, and map scale and zoom factors are set by the navigation range settings.

¹⁹² The Data Transfer System (DTS) is the method by which the mission data is transferred to the aircraft.



UH-60M

CH-47F

AH-64D

Figure 118. UH-60M (top), CH-47F (bottom, left), and AH-64D (bottom, right) digital moving map displays.

The UH-60M TAC MAP mode is presented in Figure 119. This mode provides for the display of various tactical situation awareness information, which include a digital map underlay, a standard military symbology underlay, and an active threat display. An additional sub-mode provides the ability to actively display, edit, and modify flight plans and symbol entity data. Note the composite use of color in the map background and features, as well as bezel key label backgrounds and text.

Bezel keys around the MFD screen (Figure 118, top) are used to select desired map configuration, overlays and orientation. The map has a cursor that can be controlled by multi-function slew controllers (MFSC) positioned on each side of the center console (Figure 120, left) and a collective slew controller (CSC) mounted on each pilot's collective control (Figure 120, right). The slew buttons (indicated by the red arrows) on each controller are white in color.



Figure 119. UH-60M TAC MAP.



Figure 120. UH-60M DMS multi-function slew controllers (MFSC) positioned on each side of the center console (left) and a collective slew controller (CSC) mounted on each pilot's collective control (right). Red arrows denote the position of the white cursor slew buttons.

There are the cursor modes possible with the TAC MAP: FREE, BEZEL, and MENU. The default cursor (FREE mode) is a magenta crosshair (Figure 121b) (shown here against a white background). This is the appearance the cursor takes on when there are no symbols active. As is the case of the white aircraft symbol (Figure 120a), this cursor may be difficult to see against the multi-colored map. When the cursor is transitioned into the BEZEL cursor region, it is displayed in cyan (Figure 121c). When the cursor is positioned to capture a symbol, that symbol changes color to green and a green box is drawn around the symbol (Figure 121d).

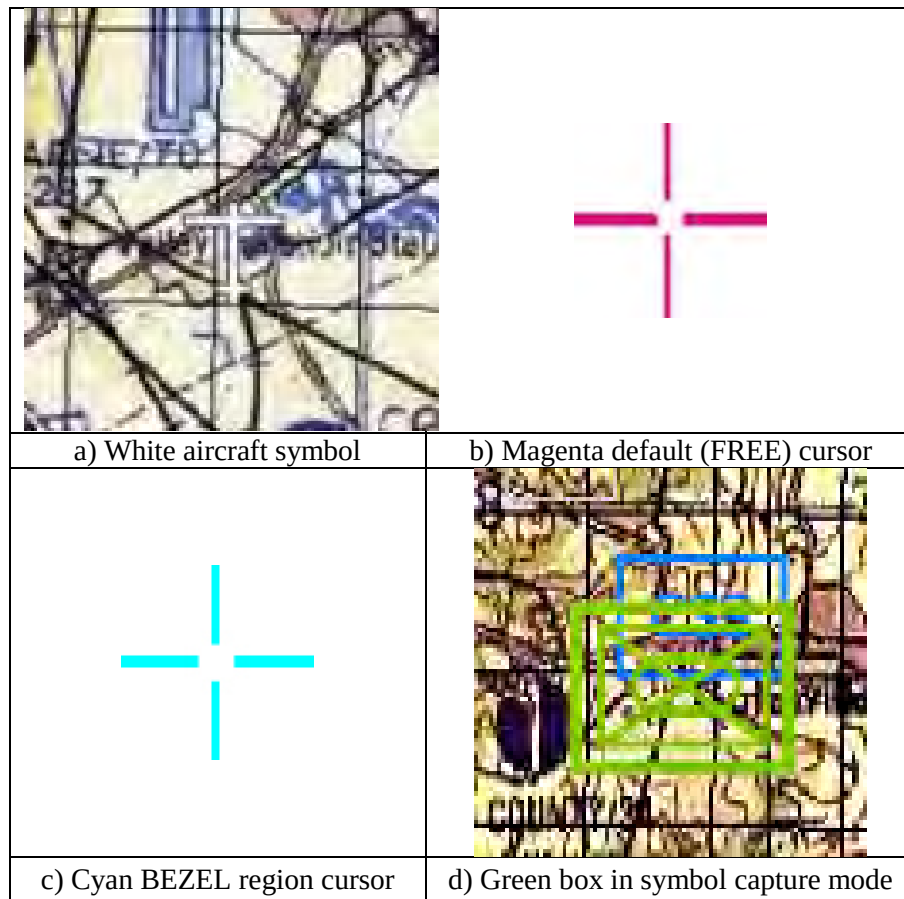


Figure 121. Cursor color changes with cursor mode.

Another use of color in the TAC MAP is for height above terrain (HAT) (Figure 122).¹⁹³ The MFD allows control of HAT shading and elevation banding via selection of four modes: elevation banding, warning elevation, warning and caution elevation, and an off mode. The default HAT mode at power-up is warning and caution elevation. The warning elevation mode displays red tinting for areas that are above the current aircraft barometric altitude. The caution elevation mode displays yellow tinting for areas that are below the current aircraft barometric altitude but above a specified height delta.

Anatomy and Physiology of Color Vision

The human eye is a complex structure designed to gather a significant amount of information about the environment; for aviators, this is both inside and outside the cockpit. If there is a beginning to the illusion of color, a good place to find it is in the human eye. For it is there the spectral energy the brain finally interprets as color is first acquired. This acquisition of light energy, which occurs in the retina, is where color vision is initiated. In a simplistic representation, all aspects of vision (including color vision) can be separated into two mechanisms: one encompassing image formation (i.e., the collection and focusing of light on the

¹⁹³ The HAT acronym also may be used as *height above touchdown*.

photoreceptors in the retina at the back of the eye) and one consisting of the physiological and cognitive processes that follow (Salmon, van de Pol, & Rash, 2010).

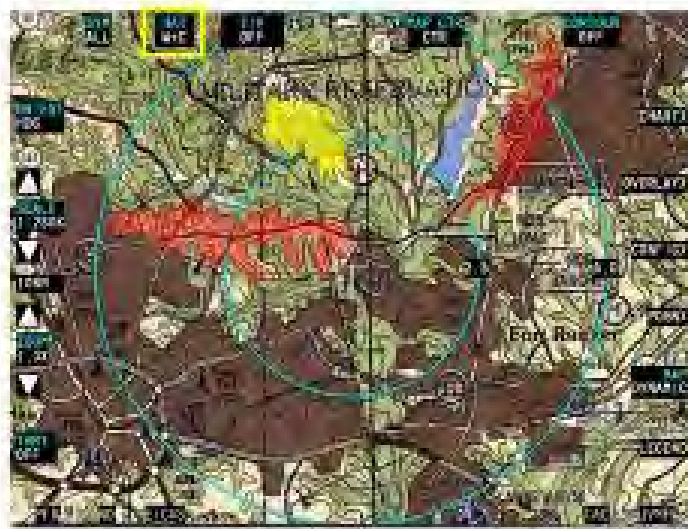


Figure 122. Height above terrain (HAT) color tinting, (The yellow frame box has been artificially added to highlight the “HAT W+C” selection.).

Image formation.

In Figure 123, a simple object of interest, a tree, is depicted on the left. As an illuminous object, the tree can be seen only when light from a source such as the sun, moon, or artificial source falls upon the tree and is reflected. Light will be reflected from, and can be considered as originating from, every point on the tree. It is convenient to treat light as originating from each point as rays that travel in straight lines. Only those rays entering the eye are important for this discussion. Furthermore, due to the nature of optics, only a representative number of these rays need to be considered in order to investigate the image formation process. In Figure 123, three rays have been depicted, one each from the top, middle, and bottom of the tree.

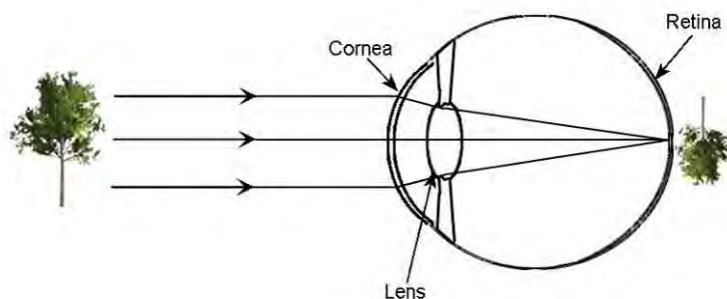


Figure 123. Formation of an image within the human eye.

In this basic model, the eye uses a simple lens system (cornea plus the lens) to form an image of the tree on the retina. In an often-used analogy, the eye is compared to an old-fashion analog film camera. In this analogy, the retina acts as the film, the lenses of the eye acts as the lenses of the camera, and the iris acts as a diaphragm controlling the amount of light entering the eye-camera. Except for those entering along the optical axis of the eye, the light rays are refracted (bent) by the lenses and focused onto the retina. When rays from all points of the tree are considered, a two-dimensional image of the tree, although inverted, is formed on the retina (Figure 123). The brain later turns this image “right way up” in the stages leading up to conscious perception.

Note the eye’s optical system includes two lenses, the *cornea*, at the front of the eye, and the *lens*, inside the eye. The cornea acts as a fixed-focus converging lens, providing approximately 75% of the focusing power of the eye; the internal crystalline lens acts as a variable focus lens. It is controlled by a set of muscles (the ciliary muscles) that relax and contract, thereby changing the lens’ curvature and power. This mechanism provides the fine-focusing that allows the cornea-lens system to form a sharp image on the retina over a range of object distances (Bennett & Rabbetts, 1991; Atchison & Smith, 2000; Goss & West, 2002; Benjamin, 2006;

Eye anatomy.

Anatomically, the human eye has protective structures (i.e., the orbit, lid, and sclera); a front section (called the anterior segment), consisting of the cornea, aqueous humor, iris, (crystalline) lens, and ciliary muscles; and a rear section (called the posterior segment) consisting of the retina and the vitreous humor (Figure 124) (van de Pol, 2010).

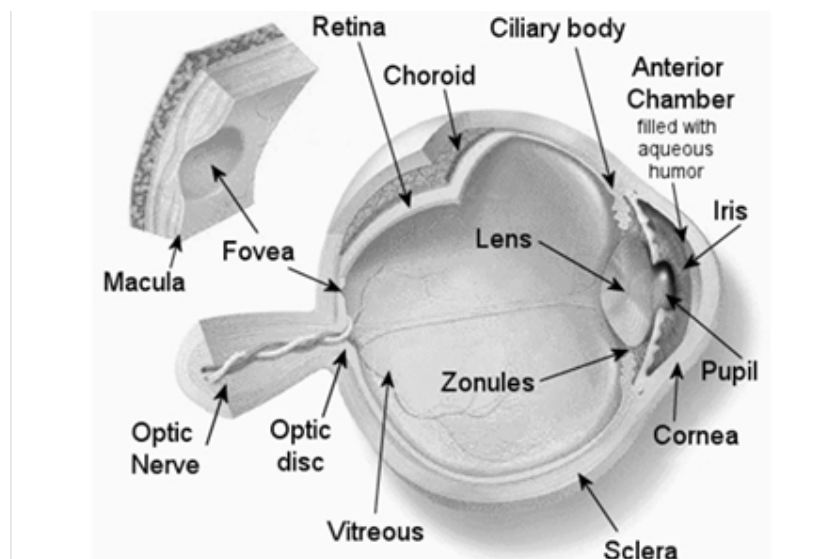


Figure 124. Anatomy of the eye. (http://www.gimbeleyecentre.com/images/Cross_Section_Labelled.gif).

Protective structure of the eye.

Each of the two eyes (globes) is approximately 0.94 inches (in) (24 millimeters [mm]) in diameter and is located in a socket (orbit) at the front of the skull and occupies about 25% of the volume of the orbit, allowing space for the extraocular muscles, blood vessels, nerves, and orbital fat and connective tissue that surround and support the eye. The orbit surrounds and supports most of the eye, while the cornea and part of the anterior globe extend somewhat beyond the orbital rims. These structures are protected by the eyelids. The globe itself is predominately formed of and protected by the sclera that extends from the edges of the clear cornea at the front of the eye (the “limbus”) to the optic nerve at the back of the eye. The sclera is a thick, opaque white tissue covering 95% of the surface area of the eye. The sclera also serves as the anchor tissue for the extraocular muscles, a set of six muscles that control the movement of the eye (and one that controls eyelid elevation).

Anterior segment of the eye.

The portion of the eye visible without special instrumentation is the anterior (or front) segment of the eye. Most of the structures responsible for focusing images onto the retina are located here, e.g., the cornea and crystalline lens.

The cornea is a unique biological tissue that is virtually transparent to light and contains no blood vessels. This small transparent dome at the front of the eye is approximately 0.43 in (11 mm) in diameter and approximately 500 microns (μm) thick in the center, thickening to around 700 μm at the periphery.

The aqueous humor fills the anterior segment of the eye, that region between the cornea and the front surface of the lens. The aqueous humor has two functions: it provides nutrients to the cornea and is part of the optical pathway of the eye. It is a transparent fluid with an index of refraction of 1.333, which is slightly less than the index of refraction of the cornea (1.376) and less than the index of refraction of the lens (gradient index of 1.406 to 1.386). It is these differences in indices of refraction between media coupled with the curvature of the various optical surface interfaces that result in the bending of light at each interface.

The iris controls the aperture (or pupil) of the eye for vision at different light levels. The iris is actually an extension of the ciliary body, a structure having multiple functions in the anterior segment, from production of the fluid known as the aqueous humor to suspension and control of the shape of the lens of the eye. The iris is visible through the cornea and is what gives the eye its “color.” The main purpose of the iris is to block excess light from entering the eye and to control the size of the pupil for differing levels of ambient light. There are two opposing muscles in the iris; the sphincter muscles that serve to constrict the pupil and the dilator muscles that serve to dilate the pupil. The pupil’s diameter is usually close to 4 mm, but in dim illumination it can dilate to about 7 mm, and in bright illumination it constricts to about 2 mm. Pupil sizes varies somewhat from person to person, and with age, race, distance of the object being viewed, emotional state, fatigue and in response to certain drugs (Birren, Casperson, & Botwinick, 1955; Fry, 1945; Hess, 1972; Winn, Elliott, Whitaker, & Phillips, 1994). Pupil size

also affects retinal image quality. A small pupil increases the eye's depth of focus and minimizes the effect of small optical errors.

Like the cornea, the crystalline lens is a transparent structure. Unlike the cornea, it has the ability to change its shape in order to increase or decrease the amount of refracting power applied to light entering the eye. Transparency is maintained by the regularity of elongated fiber cells within the lens. These cells originate at the equator of the lens and lay down across the surface of other fiber cells while growing toward the anterior portion of the lens and the posterior portion of the lens until they meet at the central sutures. During elongation they pick up crystallins (a protein), hence the name "crystalline lens." It is these crystallins that give the lens a higher index of refraction than the aqueous and vitreous humors. The gradient index of refraction of the lens ranges from about 1.406 through the center to about 1.386 through the more peripheral portions of the lens (Hecht, 2002).

Posterior segment of the eye.

The retina lines the interior of the posterior portion of the globe and is where images are formed. Initial processing of the image occurs at this highly specialized sensory tissue. Vitreous is the clear gel that fills the posterior segment and serves to provide for light transmission through the eye and to protect the retina.

The retina is a mostly transparent thin tissue designed to capture photons of light and initiate processing of the image by the brain. The average thickness of the retina is 250 μm and consists of 10 layers. Near the back of the retina are the photoreceptors. There are two types of receptors, *rods* and *cones*, essentially named for their shape (Figure 125). The outer segment of the receptor cells contain light sensitive visual pigment molecules called opsins. There are approximately 5-7 million cones and 92 million rods in the normal adult retina. Cones provide the ability to discern color and to see fine detail and are more concentrated in the central part of the retina (the fovea). Rods are mainly responsible for peripheral vision, motion detection, and vision under low light conditions; they are more prevalent in the mid-peripheral and peripheral retina (Figure 126). The distribution of rods and cones are interrupted in the nasal retinal region by the position of the optic disc (the exit point for the optic nerve); there are no rods and cones in this area, and it is known as the *blind spot* – a hole in the eye's vision).

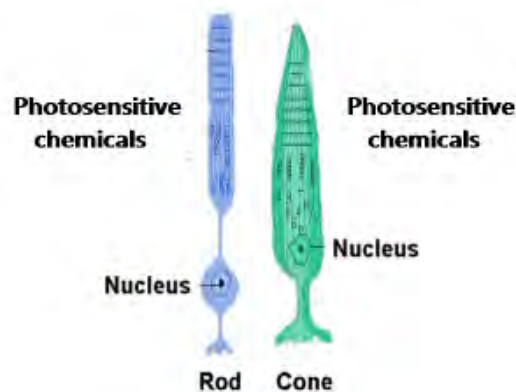


Figure 125. Rod and cone photoreceptors found in the retina.

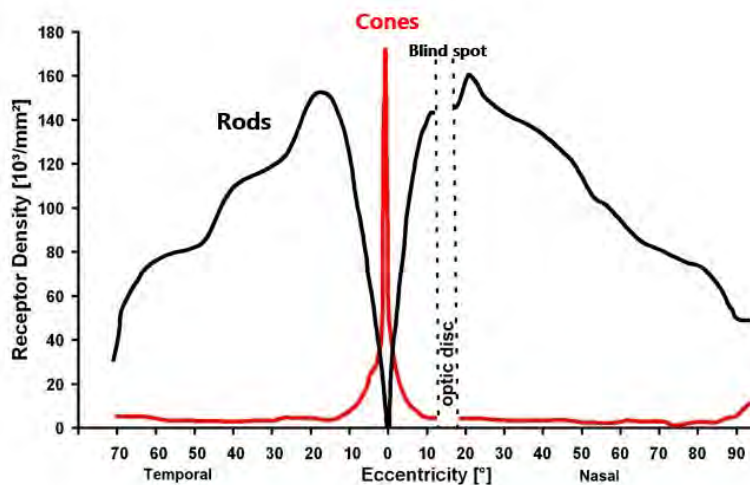


Figure 126. Distribution of rods and cones in the retina (modified from Osterberg, 1935).

Photoreceptors.

Rods are the more prevalent type of photoreceptor and contain the photosensitive pigment rhodopsin. Rods have a peak sensitivity at approximately 498 nm and are far more sensitive to light, being able to respond to a single photon (Figure 127).¹⁹⁴ The cones exist in 3 types, defined by the absorption characteristics of the 3 different types of pigments they may contain. Out of the 5-7 million cones in the retina, 62% are considered “red” or long wavelength cones (L-cones); 31% are considered “green” or medium wavelength cones (M-cones); and 7% are considered “blue” or short wavelength cones (S-cones). This density distribution is represented in Figure 128 (; Roorda & Williams, 1999; Roorda, Metha, Lennie, & Williams, 2001).

L-cones have a peak sensitivity at approximately 564 nm; M-cones peak near 533 nm; and S-cones peak near 437 nm (Wald, 1964). It is important to note the common use of “red,” “green,” and “blue” cone nomenclature is slightly misleading, as each of the three cone types have photosensitive pigments that absorb over a relatively wide band of visible wavelengths (Figure 127). In general, the S-cones produce a response over the spectral range 400-500 nm; the M-cones respond over the range 450-630 nm; and the L-cones over the range 500-700 nm (Hunt, 2004). Therefore, as examples:

- Light entering the eye at 475 nm would cause a response in both the S- and M-cones;
- Light entering the eye at 500 nm would cause a response in all 3 cone types;
- Light entering the eye at 550 nm would cause a response in both the M- and L-cones; but
- Light entering the eye at 650 nm would cause a response only in the L-cones.

¹⁹⁴ However, perceptual awareness requires simultaneous absorption of at least 10 photons (Cornsweet, 1970).

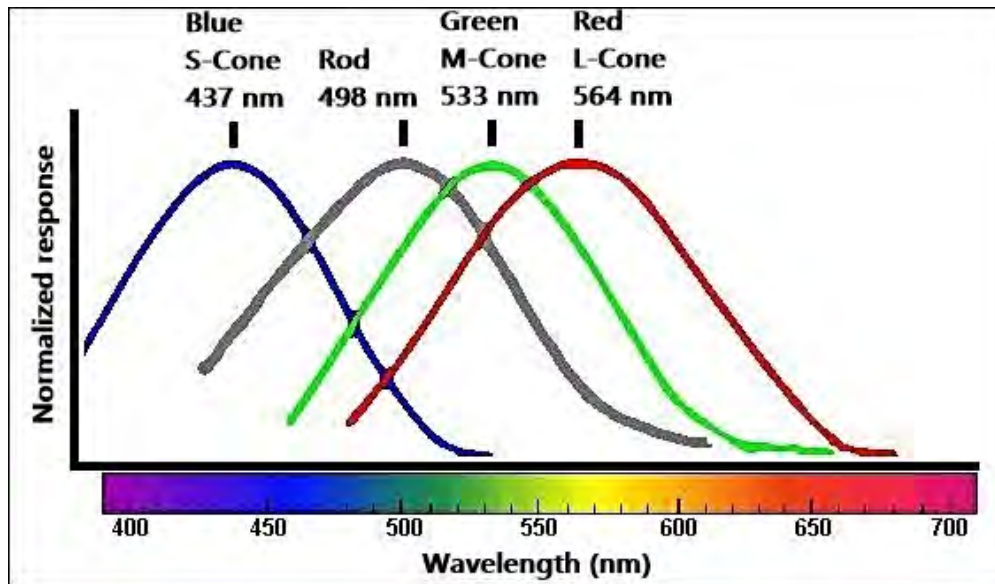


Figure 127. Relative response curves for rods and cones.

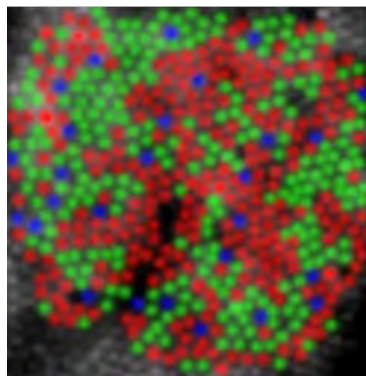


Figure 128. Distribution of S-, M-, and L-cones in the paracentral retina of one subject. Blue, green, and red dots, respectively, show the locations of S-, M-, and L-cones in a 136 μm x 136 μm (0.5° x 0.5°) region on the retina. Calculated from data provided by A. Roorda.

The overlapping across different absorption spectra of the three cone types makes it possible to uniquely encode any wavelength by the ratio of three cone responses. The three cone types send their signals into a complex network of neurons within the retina that further process the wavelength (chromatic) and brightness (luminance) information and send it to the brain, where the perception of color is completed (Schwartz, 2004).

Photopic, mesopic, and scotopic vision.

Humans can see over a light intensity range in excess of a billion to one ($\sim 10^5$ to 10^{-4} lux¹⁹⁵). This is the eye's static range; however, at any given time, the eye only can see a range of

¹⁹⁵ The *lux* (lx) is the SI derived unit of illuminance. It is equal to one lumen per square meter. In photometry, it is used as a measure of light intensity, as perceived by the human eye.

approximately a thousand to one (i.e., the eye's dynamic range). In order to achieve this, the eye adjusts to the prevailing lighting conditions (i.e., via pupil size) and changes its mode of operation (cones to rods) as light levels decline from bright day to dark night. The rods and cones operate differently over changing ranges of ambient illumination. Vision in these ranges (in decreasing levels of illumination) are referred to as photopic vision, mesopic vision, and scotopic vision (Figures 129 and 130).

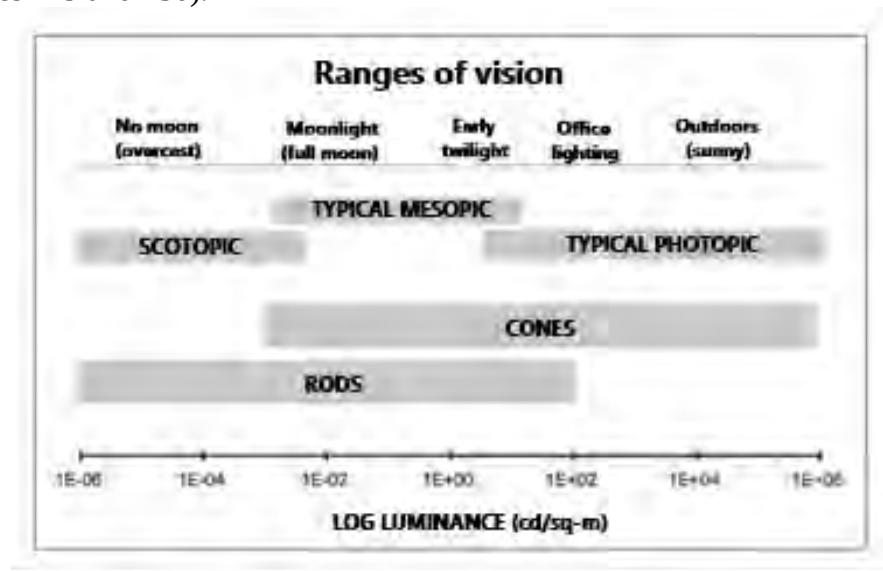


Figure 129. Ranges of vision for rod and cone operation.¹⁹⁶

Cones operate best in high illumination, and this type of vision is known as photopic vision, which is characterized by relatively low light sensitivity, high visual acuity, high temporal response, and excellent color vision. Most daytime activities, indoors and outdoors, occur using photopic vision. Photopic vision is induced by the presence of sunlight and artificial lighting. Light levels above approximately 3 cd/m² generally are accepted as in the photopic range.

Rods operate best in very low illumination, i.e., scotopic vision. At higher levels, they become saturated. Scotopic vision occurs at very low light levels and exhibits: use of rod photoreceptors, high light sensitivity, reduced visual acuity, and virtually no color vision (monochromatism).¹⁹⁷ However, scotopic vision, which has an upper limit at the illumination level associated with an overcast moonless night, is less commonly encountered in today's world where lights are everywhere. Pure scotopic vision occurs only when there is no significant light source. Almost any indoor or outside lighting (including moonlight) prevents full scotopic vision (Green, 2013). Scotopic light levels are generally defined as less than 0.01 cd/m². Experimentally, the threshold for rod stimulation is on the order 10⁻⁶ cd/m²,¹⁹⁸ below which the eye's perception is of total darkness (Pirenne, Mariott, & O'Doherty, 1957).

¹⁹⁶ Luminous intensity is expressed in the SI unit of candela; candelas per square meter is a unit of luminance.

¹⁹⁷ Some research supports color perception as possible under dim, scotopic illumination via different physiological and perceptual mechanisms other than the standard trichromatic color model (Elliott & Cao, 2012). Results challenge the classic view that rod vision is achromatic and suggest scotopic hue perception is mediated by cortical processes.

¹⁹⁸ This threshold value will vary with light source geometry and spectral content (Davson, 2012).

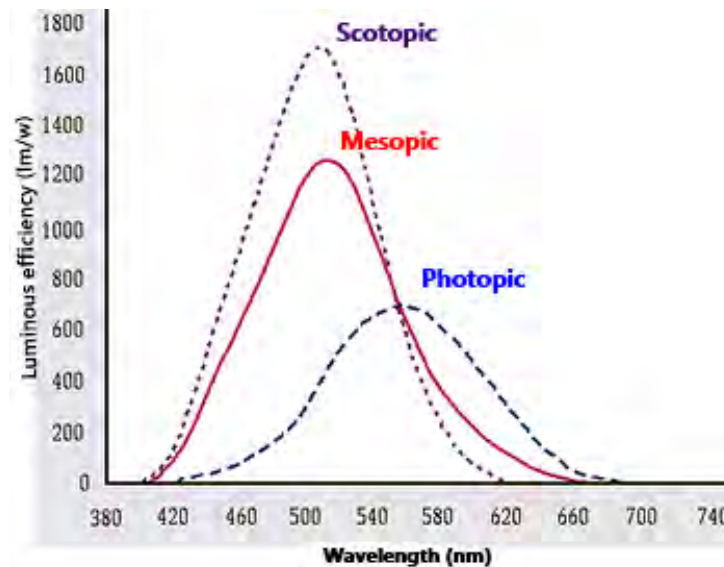


Figure 130. Spectral ranges of photopic, mesopic, and scotopic vision.

The differences between photopic and scotopic vision impact the human visual system in several ways (Narisda & Schreuder, 2004):

- Photopic vision is restricted mostly to the fovea and the near periphery;
- Scotopic vision is mostly effective in the near and far periphery;
- Visual acuity is much greater under photopic vision than under scotopic vision;
- Color vision is effectively not possible under scotopic vision;
- With photopic vision, peak sensitivity occurs at a much longer wavelength than in scotopic vision (i.e., the Purkinje shift);
- Scotopic vision is more sensitive to blue light and less sensitive to red and yellow light than photopic vision.

Photopic vision peaks at approximately 555 nm; scotopic peaks at approximately 507 nm (Figure 130). This difference in spectral response is known as the Purkinje shift. This shift occurs as the eye transitions from day vision to night vision and vice versa. One interesting consequence of the Purkinje effect¹⁹⁹ is as nighttime conditions set in, longer wavelength colors (reds) of light will appear darker and shorter wavelength colors (blues) will appear relatively brighter. This causes red objects to become more difficult to see at night than blue or green objects with similar reflectances (Schwartz & Krantz, 2015).

In between photopic and scotopic vision is mesopic vision (Figure 130). Mesopic vision operates over a range of light levels where both cones and rods are contributing to vision. There are no hard-line transition points at either end, but generally the mesopic range is considered to be from approximately 3 cd/m² down to 0.01 cd/m². At night, many outdoor artificial lights produce light levels in the mesopic range. Under natural light sources, this range would run from early twilight to nearly full moon lighting levels. When both rods and cones are operational, rods

¹⁹⁹ This effect has discovered in 1819 by Johann Purkinje (1787-1869), a Czech anatomist and physiologist.

influence many aspects of color vision (Montag & Boynton, 1987; Buck, 1997). The perception of color in mesopic vision differs considerably from that in photopic vision, where only cones are operating (Nagel, 1924; Shin, Yaguchi, & Shioiri, 2003). A number of studies have looked at color perception under mesopic vision (Stabell & Stabell, 1994; Ishida, 2002). Several studies have revealed the existence of an interaction between cones and rods in color vision (Shin, Yaguchi, & Shioiri, 2003).

For aircrew using I² devices, the brightness of the image can result in photopic or mesopic vision in viewing and interpreting the image content for the central 40° of their visual field, while depending on scotopic vision to scan for objects in the far periphery. The wide variation in mesopic vision capability likely means that some users may not see as much detail in the image as others (Salazar, Temme, & Antonio, 2003).

The visual system pathway.

Luminance and color play separate roles in vision and are processed in different subareas of the retino-geniculo-cortical pathway (De Valois, Abramov, & Jacobs, 1966; Spering, Montagnini, & Gegenfurtner, 2008). Color signals derive from differences in activity in the S-, L-, and M-cones, while action in the luminance channel is derived from the addition of the different cones signals (Vergeer, Antis, & van Lier, 2015).

The neural processing of visual information is quite complex even within the retina, but becomes even more so as the information proceeds on its pathway within the brain (Pinera, 2005). The neural signals initially processed by the retina travel via the axons of the ganglion cells (Figure 131) through the optic nerves, dividing and partially crossing over into the optic chiasm and then travelling via the optic tracts to the lateral geniculate nucleus (LGN).²⁰⁰ From the LGN, the signals continue to the visual cortex, where further visual processing takes place (Figure 132).

The visual cortex in the occipital lobe of the brain is where the final processing of the neural signals from the retina takes place and “vision” occurs. The occipital lobe is at the most posterior portion of the brain (Figure 133, left). There are a total of six separate areas in the visual cortex, known as the V1, V2, V3, V3a, V4, and V5 (Figure 133, right).

The primary visual cortex (V1) is the first region in the visual cortex where the neurons from the LGN fire across the synapses. In V1, the neural signals are interpreted in terms of visual space, including the form, color, and orientation of objects. V1 dedicates most of its area to the interpretation of information from the fovea. This mapping is known as “cortical magnification” and is typical in primates and animals that rely on information from the fovea for survival. The signals then pass through to V2 where color perception occurs and form is further interpreted. As the neural signals continue further into other areas of the visual cortex, more associative processes take place.

²⁰⁰ The retina has two classes of ganglion cells constituting parallel pathways: a) The magnocellular pathway originating in large ganglion cells with large receptive fields. Cells in the magno pathway are not sensitive to color but are sensitive to motion; b) The parvocellular pathway originating in small ganglion cells with small receptive fields. Cells in the parvo pathway are sensitive to color and fine detail.

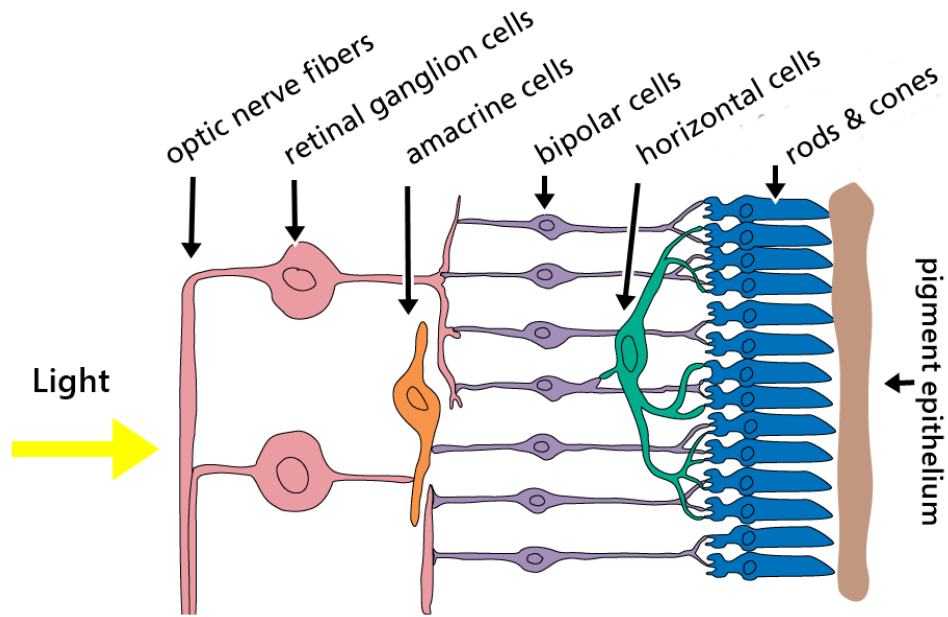


Figure 131. Schematic showing cells in the retinal processing of light.

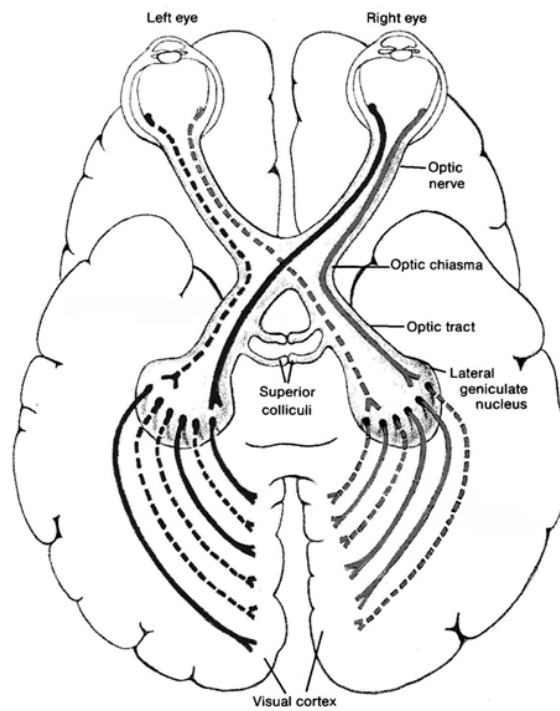


Figure 132. Visual system pathway (<http://www.skidmore.edu/~hfoley/images/Brain.top.jpg>).

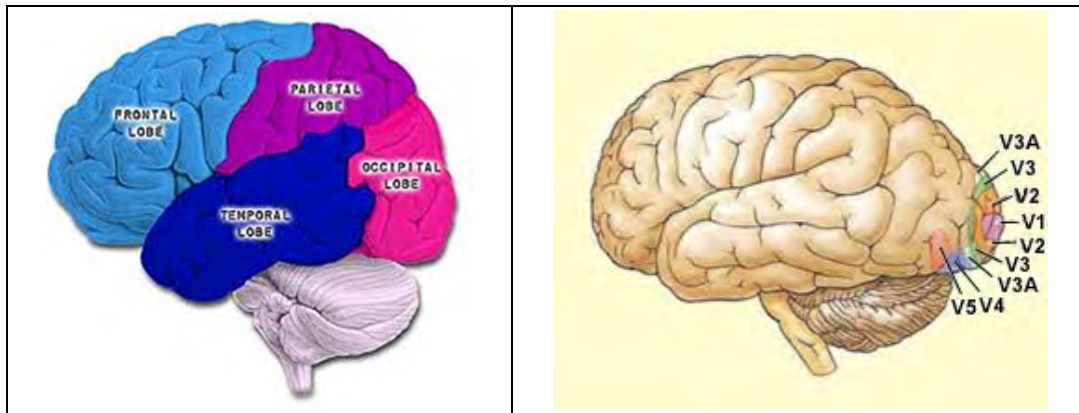


Figure 133. Lobes of the brain (left), including the occipital lobe, containing the primary visual cortex (V1) and other visual cortices.

Only within the last couple of decades has it become clearer how the primary visual cortex (V1) contributes to color vision. It was known neural signals carrying information about color arrived at the cortex from the retina and relayed through the LGN. However, it was unknown exactly how V1 acts on the color signals received from the LGN (Shapley & Hawken, 2002). It is possible these different color mechanisms may contribute separately to the perception of color boundaries and colored regions. Many cells in V1 respond to color and to luminance patterns. These neurons are spatially selective and may provide information about boundaries between dissimilar regions of color. Other V1 neurons preferring color over luminance respond without much spatial selectivity to colored stimuli and could be the basis for the response to local color modulation. How these different types of color cells combine inputs from cone photoreceptors is what gives them their different spatial selectivity for color. Shapley & Hawken (2002) believe “the existence of these different types of color transformation in V1 may help to explain the richness and apparent complexity of color perception.”

While not universally accepted, the study of individuals with lesions suggest additional specialization of the cortical regions with respect to color: V1 and V2 at early stages respond to color, V3 and V3a respond to form (especially in motion) but not to color, and V4 responds to color and line orientation (Zeki, 1992, 2001; Schiller, 1996; Simos, 2001).

Color vision theories.

Two theories dominate attempts to explain how color vision works. These two theories are the Young-Helmholtz trichromatic theory (after work by Thomas Young [1802] and Herman von Helmholtz)²⁰¹ and the Hering opponent process theory (after work by Ewald Hering [1878]).

With the Young-Helmholtz trichromatic theory of color vision, there are three receptors in the retina, each having a different peak sensitivity, that are responsible for the perception of color. One receptor is sensitive to the color green, another to the color blue, and a third to the color red. Evidence for the trichromatic theory comes from color matching and color mixing

²⁰¹ The trichromatic theory of color vision was greatly assisted by work by James Clerk Maxwell in color matching and by John Dalton's investigation of color vision deficiencies.

studies. However, several color perception phenomena cannot be explained by the trichromatic theory alone. One of these phenomenon is complementary color afterimages, in which the extended observation of one color will lead to the subsequent perception of its complementary color. The complementary afterimages are better explained by the opponent-process theory. (Perform the demonstration of the American Flag afterimage illusion in Figure 134).

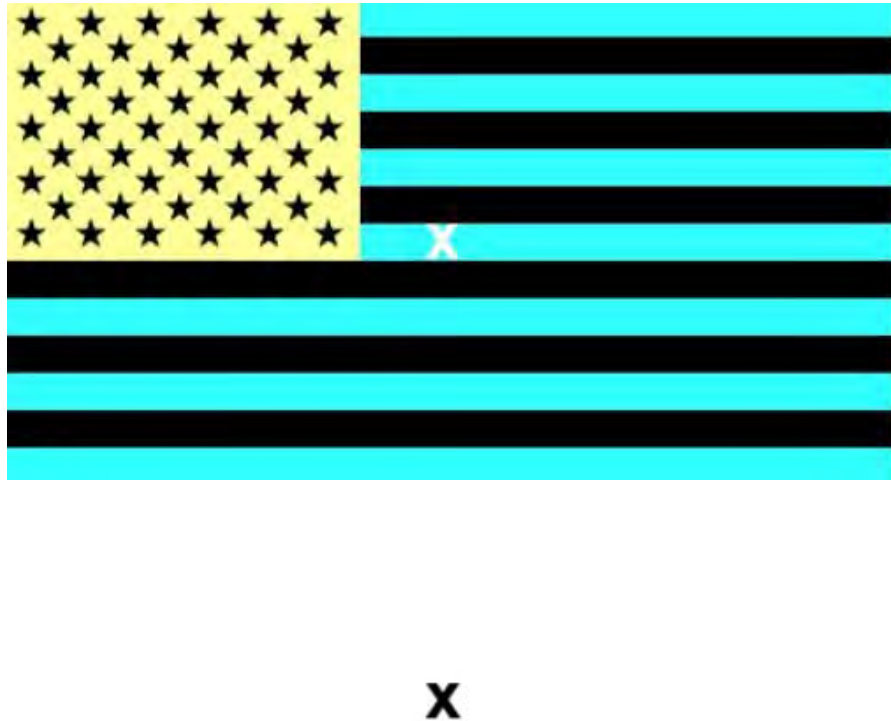


Figure 134. Demonstration of color afterimages. If the middle of the cyan, black, and yellow flag image (top) is stared at without blinking for 30 seconds, and then the eyes quickly look at a white area (bottom), the normal red, white, and blue (complementary colors) of the American flag will appear briefly.

As demonstrated with color afterimages, even though the trichromatic theory is able to explain a large part of human color vision, there are still some aspects that it cannot explain (Jetsu, 2010). Another example is the situation where CVDs are associated with certain pairs of colors (e.g., red-green or blue-yellow) instead of individual colors. And, why under normal viewing conditions do such colors as reddish-green or bluish-yellow not exist (Crane & Piantanida, 2010).

In the opponent process theory, Hering stated that instead of three, there are actually four different primaries (red, green, blue, and yellow), and these primaries appear in pairs (red-green

and blue-yellow) (Figure 135). According to Hering, color processing is based on three main components that respond in two opposite directions to signals: red vs. green, blue vs. yellow, and black vs. white (i.e., activation of one color of the pair results in the inhibition of the other). His theory explains the inability to see bluish-yellow as being prevented by the blue-yellow cells, which are excited by wavelengths in the blue part of the visible spectrum but inhibited by those in the yellow part of the spectrum (Gray, 2002).

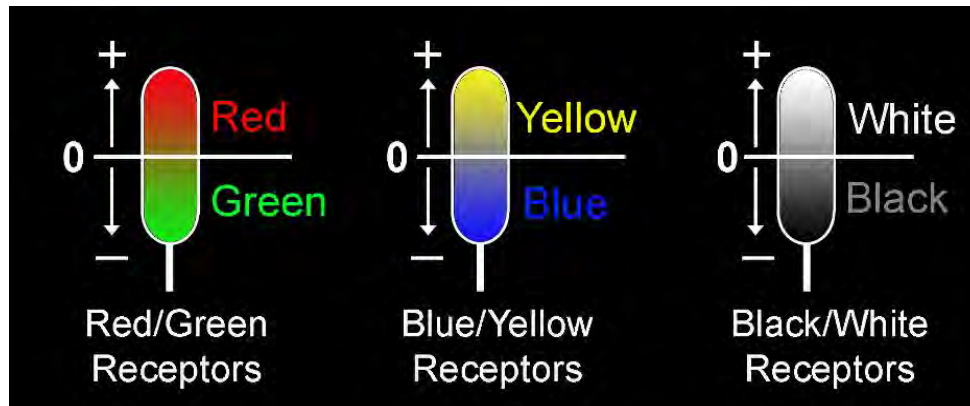


Figure 135. Pairs of opposing cells in Hering's opponent process theory of color vision (Source: Stephen E. Palmer, 2002).

The inconsistencies between the trichromatic and opponent process theories were a continuing problem for decades (Mather, 2016). Until at least the mid-1950s, it was common for authors to portray the two theories as rivals. But, actually both theories help to explain how color vision works. The trichromatic theory operates at the receptor level, and the opponent processes theory applies to the subsequent neural level of color vision processing.

In 1957, Hurvich & Jameson developed a dual-process theory, a fusion of the trichromatic and opponent process theories. Color vision is asserted to contain two stages: an initial trichromatic stage and a later opponent-process stage. In this combined theory, signals from the three cone types are sent to opponent cells. The difference in the activity of types of cones is processed along three channels: achromatic, blue–yellow, and red–green. Acceptance of this theory is restrained, as many consider this theory an oversimplification of color perception (Eysenck & Keane, 2015).

The dual-process theory is an example of a group of *zone* theories of color vision developed from the 1930s to 1960s that attempted to bring together the basic tenets of the Young-Helmholtz trichromatic and the Hering opponent theories. The properties of both theories are combined into two separate but sequential zones that describe the process of light arriving at the retina (Judd, 1949; Massof & Bird, 1978).

In addition to the trichromatic, opponent, and zone theories, there also have been other approaches to explaining color vision. One of the better-known is E. Land's Retinex²⁰² theory first introduced in 1964 and the further developed by Land and McCann (Land & McCann, 1971;

²⁰² Retinex is a portmanteau formed from "retina" and "cortex", suggesting that both the eye and the brain are involved in the processing.

Land, 1977, 1986). This theory assumes the three independent cone systems of the trichromatic theory. Each system forms a separate image of the world in terms of lightness that shows a strong correlation with reflectance from an object within its particular band of wavelengths. These images are not mixed but instead compared to generate color sensations. Land states “The problem then becomes how the lightness of areas in these separate images can be independent of flux.” He developed a mathematical algorithm for a lightness scheme that generates lightness numbers, a biologic correlate of reflectance, independent of the flux from the object. Land’s Retinex algorithm is one model of human color constancy, one of the fundamental features of human color vision (see *Color Perception* section). However, some researchers argue the algorithm is too sensitive to changes in the color of nearby objects to serve as an adequate model of color constancy (Brainard & Wandell, 1986).

Color vision deficiencies (CVDs).

The majority (~96%) of individuals have normal color vision capabilities; they are referred to within the vision community technically as *trichromats* and colloquially as *color normals* (i.e., can perceive all of the three primary colors). However, a significant number of individuals have a CVD. CVDs can be hereditary, acquired, or induced artificially. Congenital (genetic) color deficiencies are almost always red-green and are considerably more common in males, whereas blue-yellow defects affect both sexes equally and are almost always a result of ocular disease or toxicity (Tredici & Ivan, 2008). (See also *Color Vision Tests and Standards* section.)

Statistics for hereditary (genetic) color defects are well known. Red-green defects are the most common form of CVD (Piantanida, 1991). A red-green color deficiency (dichromatism) is passed from mother to son on the 23rd chromosome, which is known as the sex chromosome because it also determines the sex of the offspring. Among populations with Northern European ancestry,²⁰³ it occurs in approximately 1 in 12 males (~8%) and 1 in 200 females (~0.4%). Blue-yellow color vision defects are far less common and affect males and females equally. This condition occurs in less than 1 in 10,000 people worldwide (~0.01%) (NIH, 2017).

Since the total absence of one or more of the three cone types is rare, the vast majority of individuals with hereditary CVDs are in reality “color weak,” exhibiting a partial inability to distinguish colors as the result of one or more of the three cone types functioning abnormally (i.e., altered spectral sensitivity). Three varieties of inherited anomalous trichromacy are defined: protanomaly, deuteranomaly, and tritanomaly (Figure 136).

Protanomaly (present in 1% of males and 0.02% of females), a result of the malfunctioning of L-cones, is referred to as “red-weakness.” Any red color as would be perceived by an individual with normal color vision is perceived more weakly by the protanomalous viewer, both in terms of its saturation and its brightness. Red, orange, yellow, and yellow-green colors will appear somewhat shifted in hue toward green, and all will appear paler than as perceived by a color normal. The red component that a normal observer would see in a violet or lavender color may not be perceived by the protanomalous observer; only the blue

²⁰³ Caucasians have the highest prevalence. African Americans, Japanese, and Chinese have about half this prevalence, and the lowest rate is found in native Africans (International Civil Aviation Organization, 2012).

component may be perceived. Under poor viewing conditions, such as when driving in dazzling sunlight or in rainy or foggy weather, it is possible for protanomalous individuals to mistake a blinking red traffic light for a blinking yellow one, or to fail to distinguish a green traffic light from streetlights or the various white lights in store signs (Wolf, Kluender, & Levi, 2006; Colorvisiontesting.com, 2014).



Figure 136. Sample image as perceived by individuals with normal color vision and with “color weak” deficiencies (adapted from Colblindor, 2014).

Deuteranomaly (present 5% of males and 0.3% of females), the result of the malfunctioning of M-cones, is considered as “green-weakness” and is the most common form of color deficiency. Similar to the protanomalous observer, a deuteranomalous observer has difficulty discriminating small differences in hues in the red, orange, yellow, green regions of the color spectrum. Errors in the naming of hues in these regions will occur because they appear shifted toward red.

Individuals with protanomaly and deuteranomaly are collectively referred to as red-green color deficient (dichromats) and generally have difficulty distinguishing between reds, greens, browns, and oranges. They also commonly confuse different types of blue and purple hues.

Tritanomaly (present in 0.002% of males and 0.001% of females)²⁰⁴ is associated with reduced blue sensitivity (blue-weakness) due to the malfunctioning of the S-cones. Tritanomalous individuals have difficulty identifying differences between blue and yellow, violet and red, and blue and green. To these individuals the world appears generally as red, pink, black, white, gray, and turquoise. A few studies indicate that tritan defects are virtually never present at birth (e.g., congenital), and the inherited forms involve S-cone photoreceptor degeneration developing later in life (Baraas et al., 2007; Neitz & Neitz, 2011).

When individuals have any type of color deficiency, certain colors appear washed-out and may be confused with other colors. They often have difficulty with many common, daily tasks such as matching clothes, selecting ripe fruits and vegetables, and reading maps. In addition, viewing, interpreting, and understanding the many forms of print (e.g., magazines and signage) and the multitude of electronic displays in today’s media-intensive world (e.g., smartphones, tablets, and computer displays) can be quite challenging.

²⁰⁴ Variation exists in reporting of these very low frequencies of occurrence.

In summary, there are several different types and degrees of inherited CVDs. Many protanomalous or deuteranomalous individuals can easily pass as color normals in everyday activities. They may make occasional errors in color names, or may encounter difficulties in discriminating small differences in colors, but typically their performance in color-related tasks is not very different from color normals...except on color vision tests (see *Color Vision Tests and Standards* section).

The interrelated terminology used for types of color vision and CVDs is quite varied. A brief summary of the terms used above and frequently encountered in the literature is provided in Table 13. It is important to emphasize the use of the term “color blind(ness)” is rarely correct as very few individuals are truly color blind (achromatopsia)²⁰⁵ (i.e., seeing only in black, white, and shades of gray) but instead have a color deficiency.

Table 13. A summary of terminology used for types of color vision and CVDs.

Color vision	Terminology	Description
Normal color vision	• Trichromatism • Trichromat	Three different fully functional color receptors related to red, green, and blue
Color blindness	• Achromatopsia • Rod monochromatism	Hereditary disorder characterized by vision of only black, white, and shades of gray
Color deficient	• Anomalous trichromatism • Dichromat • Dichromatism	One of the three cone pigments is lacking or altered in its spectral sensitivity
	• Protan • Protanopia • Protanomaly • Protanopic (red-blind) • Protanomalous (red-weak)	L-cones are missing (red-blind) or defective (red-weak)
	• Deutan • Deuteranopia • Deuteranomaly • Deuteranopic (green-blind) • Deuteranomalous (green-weak)	M-cones are missing (green-blind) or defective (green-weak)
	• Tritan • Tritanopia • Tritanomaly • Tritanopic (blue-blind) • Tritanomalous (blue-weak)	S-cones are missing (blue-blind) or defective (blue-weak)

Another method by which the color discrimination of dichromats can be analyzed is to plot on the CIE chromaticity diagram the pair of colors being confused. A line joining the confused pair forms an isochromatic line. All colors falling along this line cannot be discriminated by the observer. The three types of congenital color deficiencies (protan, deutan, and tritan) have their own specific color confusion characteristics. This concept can be

²⁰⁵ There are actually two types of *achromatopsia*: the complete type in which there are no functional cones in the retina and the incomplete type in which there are some functional cones (American Association for Pediatric Ophthalmology and Strabismus, 2017).

represented by color confusion lines in the CIE color triangle (Figure 137) (Birch, 1973, 1993; Dain, 2004). The colors along these confusion lines may look the same to the color deficient person. For dichromats and severe anomalous trichromats colors that are far apart on the confusion lines will be confused, while mild and moderate anomalous trichromats only confuse colors that are closer together on the confusion lines. These lines are unique for the three main types of color deficiencies, with the lines diverging from convergence (or copunctal) points having specific 1931 CIE color space x,y coordinates for each deficiency type (i.e., protan [0.747, 0.253]; deutan [1.080, -0.800]; tritan [0.171, 0.000]) (Birch, 1972; Colblindor, 2009).

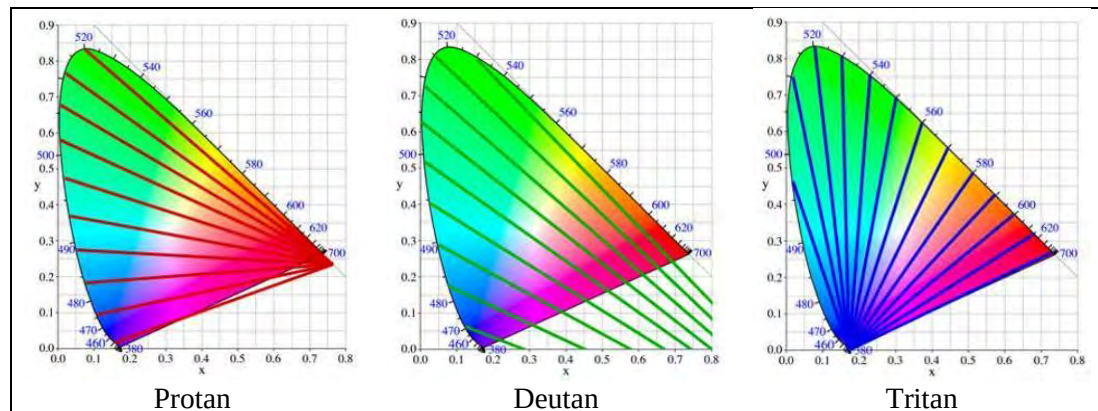


Figure 137. Confusion lines for protans, deutans, and tritans shown on CIE color diagram.

Stimuli falling along and intersecting with white on these lines will be confused with white, i.e., the appearance of these wavelengths will be white. This is referred to as the neutral point (Green, 2004a). The neutral points and colors that will be confused (as spectral distributions) for protanopia, deuteranopia, and tritanopia are presented in Figure 138. For protans, the neutral point occurs at 492 nm; above this point, they see yellows. For deutans, the neutral point occurs at 498 nm; above which, they also see yellows. For tritans, the neutral point occurs at 570 nm; above which, they see reds (Vision & Aging Lab, 2002).

Not all color vision problems are inherited. Most of these nonhereditary color vision conditions are described as *acquired* CVDs. They can be caused by eye disorders, such as diseases involving the retina, the optic nerve, or areas of the brain involved in visual information processing, as well as systemic diseases and conditions (Marre, 1973; Pacheco-Cutillas, Sahraie, & Edgar, 1999; Lau, et al., 2013). Examples include diabetic retinopathy, cirrhosis of the liver, multiple sclerosis, stroke, Parkinson's disease, Alzheimer's disease, leukemia, sickle cell anemia, and vitamin A deficiency. Acquired CVDs also can be the result of side effects of certain medications and other drugs (e.g., alcohol and marijuana), or the result of exposure to chemicals in the environment (e.g., organic solvents, carbon monoxide, and heavy metals) (Swinson, 1971; Lyle, 1974; Adams, Brown, Haegerstrom-Portnoy, Flom, & Jones, 1976; Dawson, Jimenez-Antillon, Perez, & Zeskind, 1977; Drum & Verriest, 1987; Braun & Richer, 1993; Kapitany et al., 1993; Castro, Rodrigues, Cortes, & Silveira, 2009; Besharse & Bok, 2011).

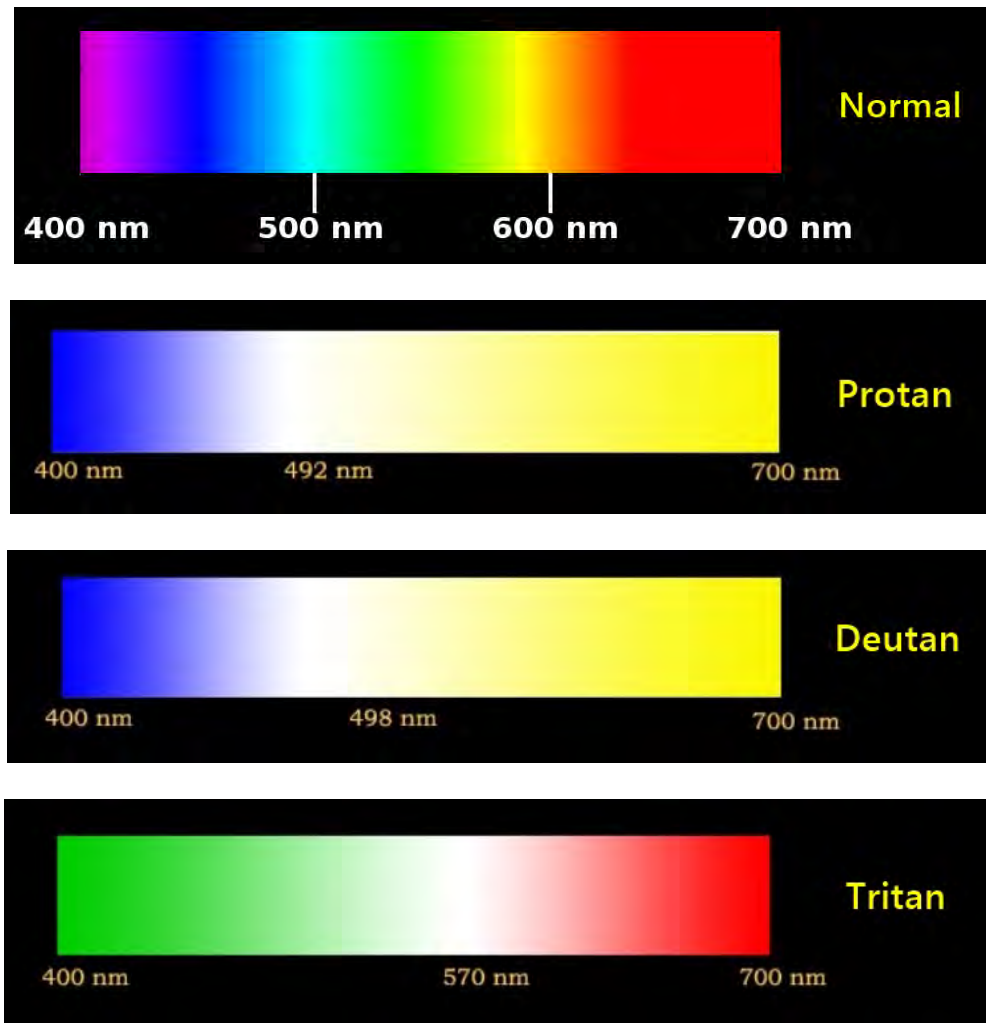


Figure 138. Neutral points and discrimination for the three types of dichromats (adapted from Vision & Aging Lab, University of Calgary, Canada [2002]).

Acquired color vision problems also can occur due to aging (Haegerstrom-Portnoy, Schneek, Lott, Hewlett, & Brabync, 2014), with the reduction in color discrimination ability primarily, but not solely, attributable to changes in the lens of the eye (Lakowski, 1962). The lens gradually becomes denser and may accumulate screening pigments, which can significantly absorb short-wavelength light, causing the lens to appear yellowish (National Research Council, 1981). As a consequence less light reaches the retina. Aging is the most common cause for acquired CVDs (Delpero, O'Neill, Casson, & Hovis, 2005).

Lastly, transient disruptions in color vision function can be induced by artificial local environmental conditions well-associated with military aviation (e.g., G-forces and hypoxia).

Operational threats to color vision.

Color vision performance at any given time is determined by congenital, physiological, and operational factors. The first set of factors is predetermined, and any such impact on

performance is hopefully identified during initial color vision testing. With the exception of aging, physiological factors can degrade color vision performance at any time and can be temporary or permanent. Such degradation can be self-identified or detected by routine visual screening.

Military aviation is frequently conducted in visually hostile environments. Consequently, there are several operational factors present, while transient in nature, that often impair or distort color vision performance (Menu et al., 2001). Examples include:

- G-forces – a color hue shift occurs during gradual onset Gz acceleration (3-5 Gz) (Allnutt & Tripp, 1998); as G forces increase climbing toward 7G, color is no longer seen, everything appears in black and white;
- Hypoxia – low retinal oxygen concentrations related to high altitude flights degrade color vision (Barbur & Connolly, 2011; Petrassi, Hodgkinson, Walters, & Gaydos, 2012);
- Gz-vibration – vibration impacts the ability to interpret color displays;
- Ambient illumination – fractured, rapidly fluctuating ambient illumination (as in rapidly maneuvering, agile aircraft) can wash out or color contrast on displays;
- Glare, direct or reflected – displays frequently must be viewed under an extreme range of illumination conditions;
- After-images – viewing of monochromatic imagery as in night vision devices can produce afterimages, transiently distorting color perception (see *Special Color Issues in U.S. Army Aviation* section); and
- Exposure to laser illumination – color vision thresholds affecting recognition of caution and warning lights can be compromised by exposure to the narrow-band spectrum of lasers.

In addition, low illumination levels, pupillary reflex lag, and delayed night-vision adaptation are compounded further by vision-protecting filters (see *Special Color Issues in U.S. Army Aviation* section). These reduce display color signal saturation and distort the color spectrum, unless the visual information is delivered “inside,” behind the filter in HMDs, helmet mounted or as a virtual display.

Most current filters are largely passive, static, broadband, neutral or wavelength specific (as in tri-stimulus filters), mimicking one-way mirrors. However, variable, energy-gated (“power window”), smart dynamic filters are under development and will have variable effects on the color spectrum transmitted through to the eye. More sophisticated active filters, input driven reflectors, vector reflectors, and photon processors (whether traps, gates, “windows,” or “fences”) will complicate the situation and further compromise reliance on stable color images.

These operational factors have been identified and some have been researched for impact on color vision performance. However, most studies have focused on effects of these factors on color normals, not on aviators with impaired color vision, i.e., with CVDs (see Issue #2 in *New and Continuing Color Issues and Future Research* section).

Color Vision “Cures” and “Remedies.”

There is no current cure for color blindness, although many advertisements can be found offering one. However, one promising research approach is gene therapy (Gudgel, 2015; Milburn, Neitz, Chidester, & Lemelin, 2015). This approach is a fast-growing area of investigation directed towards cures of many genetic disorders. Researchers have showed some success in providing trichromatic vision to squirrel monkeys using gene therapy, a first step in treatment for congenital color deficiencies in humans (Dolgin, 2009; Neitz & Neitz, 2011). Other work describes a gene therapy approach to treating achromatopsia in dogs (Komaromy et al., 2010). However, it was been pointed out gene therapy has several inbuilt complexities (Ameen & Shafi, 2017). Gene therapy involves the isolation of a specific gene, making its copies, and inserting them into target tissue cells to make the desired protein. So, there a concern the body’s immune system may react to the foreign proteins produced by the new genes.

Using technology to compensate for color deficiencies.

While there currently is no cure for color deficiencies, such conditions can be alleviated to some degree. From the invention of eyeglasses in the late 13th century, through the first widely-available commercial contact lenses and refractive surgery techniques of the 20th century, to today’s tailored displays,²⁰⁶ technology has frequently been developed to compensate for visual deficiencies (e.g., spherical refractive error, astigmatism, and higher-order aberrations), and color deficiencies are no exception (Agarwal, Agarwal, & Jacob, 2009; Archand, Pite, Guillemet, & Trocme, 2011; Pamplona, Oliveira, Aliaga, & Raskar, 2011; Segrave, 2011; Huang, Wetzstein, Barsky, & Raskar, 2014).

A number of approaches using prisms, lights, and filters have been investigated in attempts to improve color deficient vision. There are special eyeglasses and contact lenses available capable of enhancing color perception for some individuals with color deficiencies, primarily red-green. As early as the 1830s, the use of filters as a means to aid color perception was suggested (Seebeck, 1837; Sharpe & Jagle, 2001). The basic explanation for the use of any filter is colors that normally look similar to a color deficient observer can be differentiated by brightness and chromaticity differences. For example, a dichromat is not able to distinguish red from green, as both appear yellow. In a monocular configuration with the usually recommended red filter, the brightness of the green will be decreased much more than that of red, allowing the observer to alternately compare the scene through the two eyes and learn to identify the darker color as green and the lighter one as red. Moreover, observing the colors simultaneously with the naked eye and through the red lens enhances some saturated colors, causing them to appear more vibrant and lustrous (Paulson, 1980). Rudimentary investigations in such filter use has emerged periodically for decades (Roaf, 1924; Payne, 1940; Kernell, 1974; Richer & Adams, 1984). Many of the earlier filter-based approaches are summarized by I. Schmidt (1976).

In 1940s, eyeglasses consisting of two segments (an upper segment of dark-red filter glass and a lower segment of clear crown glass) were available to enable some color-deficient

²⁰⁶ The term *tailored displays* refers to the technique of achieving correction of visual aberrations via changes in the display instead of the eye (Pamplona, Oliveira, Aliaga, & Raskar, 2011).

drivers to correctly perceive amber and red traffic signal lights (Payne, 1940; Popular Science, 1940). The use of such filtering eyeglasses as a color deficiency solution frequently is cited in textbooks on color vision (e.g., Evans, 2003; Fekrat & Weizer, 2006). Examples of clinical methodologies (with self-reported effectiveness) of several types of filtered-eyeglasses has been compiled by the National Institute for Rehabilitation Engineering (NIRE), a non-profit organization that operated clinics for the development and dispensing of vision aids from 1967 through 1987 (NIRE, 2002). However, controlled studies for their effectiveness are minimal.

The investigation of tinted contact lenses for correcting of color deficiencies became an active area of research in the 1970s-1980s (Ditmars & Keener, 1976; American Committee on Optics and Visual Physiology, 1980; Paulson, 1980).

In the early-1970s, X-Chrom Corporation, Waitham, MA, began marketing a raspberry-red hard contact lens for enhancing color perception for individuals with color deficiencies (Zeltzer, 1971; American Optometric Association, 1974; Zimmerman, 1978). The X-Chrom²⁰⁷ lens was to be worn monocularly in the non-dominant eye.²⁰⁸ Acting as a red high-pass, cut-off filter, the lens absorbs most of the blue light and a large portion of green light. Because of this large amount of filtering of incoming light, users had difficulty in using the lens at night. Technical data describes the lens as having a minimum transmittance of 90% over the spectral range of 590-700 nm (X-Chrom Corporation, 1982). The operation of the lens is described as: “When a person wears the lens, he will perceive some colors correctly through the naked eye – blues, for example, if he is red-green color blind (dichromat) – but other colors, for which he has a color deficiency, will be confused. The brain learns to recognize the confusion and shift to the eye with the lens. These colors are comparably enhanced by the lens, and appear brighter. This result increases the color values of what for the uncovered eye were confused colors, and also makes objects of these colors stand out against backgrounds with which they previously blended. The corrected eye sees the colors, while the background may be perceived by the naked eye. This increases the contrast. The mind, then, continuously selects the set of impulses, from one or both eyes, delivering the most visual information.” Such contact lenses are currently available; however, a number of studies looking at the utility and effectiveness of these lenses have shown varying levels of effectiveness (Welsh, Vaughan, & Rasmussen, 1979; Welsh, 1980).

More recently, a multi-notch filtering approach has been used, targeting specific photopigments, using narrow-band filtering to remove specific wavelengths. This newest version of a filtered-eyeglass achieves the filtering via multi-layered dielectric coatings applied to the lenses. While expensive (\$300-400 for non-prescription), such eyewear has received considerable praise in the business technology press (but, primarily based on authors’ experiences) (Morrison, 2015b; Porges, 2015; Pettitt, 2016). Again, controlled studies are rare.

One diverse field having seen rapid advances in compensating for color deficiencies includes commercial software development, website imagery, and display products. Due to the massive use of colors in multimedia content for conveying visual information, it is more important than ever to make sure users perceive colors correctly to ensure accurate information

²⁰⁷ The X-Chrom lens derived its name from the X, or female, chromosome, via which mothers pass the recessive color deficiency gene to male offspring.

²⁰⁸ Ocular dominance, sometimes called eye preference, is the tendency to prefer visual input from one eye over the other, e.g., right-eye dominant.

interpretation. Hence, multimedia content with rich colors well distinguished by color normals, may sometimes cause misunderstanding to users with anomalous color vision (Halder, Roy, Chowdhury, Chattaraj, & Roy, 2015). From the commercial and entertainment communities' viewpoint, users with CVDs who have difficulties discriminating certain color combinations and color differences are potentially lost customers if ignored.

Many developers have found ways to widen their consumer base for both physical products (e.g., maps, magazines, and displays) and digital products (e.g., websites, computer applications and software for photo manipulation, video games, and data analysis) by designing them to be used and understood by individuals with CVDs (Bao, Wang, Ma, & Gu, 2008; Doliotis, Tsekouras, Anagnostopoulos, & Athitsos, 2009; Jeong, Kim, Wang, Yoon, & Ko, 2011). Software has been developed capable of being switched easily between different visual presentation options based upon the user's type of color deficiency. One approach to accomplishing this uses the principle that specific colors of objects in an image may be less important than being different (i.e., being distinguished from one another), and these difference can convey the same information or meaning as the intent of the original colors themselves. Methods to accomplish this include adding combinations of differing patterns, labels, shapes, or other visual features to distinguish between objects, meanings, or symbols, or using vastly different color schemes, patterns, shades, and contrast and brightness levels to convey different meanings (Kosslyn, Simcox, Pinker, & Parkin, 1983; Yamamoto, 2007; Green, 2014b). These methods can be permanent, often decided upon and implemented during the design phase; or, for software, options can be provided allowing the user to switch between different types of (or no) compensation for color deficiencies.

One example of a color-correction technique is a process known as daltonization,²⁰⁹ which uses the concept of confusion lines to shift the colors of an image toward those that are easier to distinguish for viewers with a specific color deficiency (Anagnostopoulos, Anagnostopoulos, Tsekouras, & Kalloniatis, 2007; Halder, Roy, Chowdhury, Chattaraj, & Roy, 2015). Confusion lines, as shown in Figure 136, indicate which colors may appear identical to the color deficient observer if there is no difference in luminance or contrast between them; these lines are unique for the three main types of color deficiencies, and daltonization methods shift colors away from these lines, especially away from the copunctal points, toward colors more visible and distinguishable for a color-deficient viewer.

The process of daltonization is an iterative method using the difference between the RGB values of the pixels in an image and the simulated RGB values of the image as perceived by viewers with a CVD, to shift the RGB values of the object toward those visible to viewers with deficiencies. After each iteration, a check is performed on each pixel to determine if the colors are different enough to be discriminable by viewers with a CVD; if not, the process is repeated using the modified pixels as the new input into the process. The values and equations used to convert the RGB values of the pixels to the LMS²¹⁰ color space, and to simulate the RGB values as seen with a deficiency, are based on those derived by Judd (1948) and others. Continuing attempts to enhance and accelerate this process include: improving methods of modifying the difference between versions to decrease the number of iterations required; and developing

²⁰⁹ Named after John Dalton, who published some of the first known papers describing color blindness (deficiencies) in 1798 (Dalton, 1798).

²¹⁰ LMS (long-medium-short) is a specialized color space based on cone responsivities.

methods capable of determining which sections of an object or image no longer need adjustment and will instead focus only on sections requiring further iterations.

In addition to daltonization, other color transformation techniques are in common use (Halder, Roy, Chowdhury, Chattaraj, & Roy, 2015) :

- RGB color contrast enhancement – a process considering the total pixels in the original image. The algorithm intensifies pixel hue by making red pixels redder and green pixels greener, as well as altering the pixels blue component; effectively only the red component remains (Michelson, 2008).
- LAB color correction – This algorithm endeavors to modify reds and greens of an image to increase color contrast (Michelson & Yun, 2012).

A measurement tool frequently used to assess the impact of a color transformation process is Delta E (Woods, n.d.). This metric determines the level to which an algorithm changes the original image, i.e. negatively disturbing the image as seen by normal viewers. It operates on each pixel in an image. This function considers two images (the original and transformed) in order to estimate the color differences between them. In the process, both images are first transformed from RGB to the LAB color space, and then the metric is calculated. One study has suggested the Delta E value for a just noticeable difference is approximately 2.3 (Sharma, 2003).

Today, the internet is a widely viewed source of all types of information. Website designers have been aggressively advocating awareness of color deficient viewers in the development of color usage guidelines for web imagery (Kyrnin, 2007; Lui, 2010). One technique designers suggest is using multiple shades of the same color to widen the range of successful detection. While providing Do's and Don'ts of color use, a frequent recommendation is not to depend on color alone for important messages and instructions (a long-recognized good HFE practice) (Macaulay, 2017). However, any effort to produce images more understandable to color-deficient viewers must consider how recolored images may appear to color normals, as such transformations may appear abnormal. From the application point of view, images must be instantaneously correctly detected and interpreted by all individuals.

Compensation for CVDs also can be applied after the development and release of software as apps, mods, add-ons; and software tools, extensions, and plug-ins. These can be official, designed and released to the public by software companies, or created by the user community and fans of the software, the latter often spread by word-of-mouth and forums and downloaded over the internet. These methods can be completely stand-alone, running and compensating for a deficiency separately from other software, or can be created to interact directly with, and to launch and run in parallel with, specific software. There are various methods to assist those with color deficiencies in the field of commercial software, allowing for greater usage of digital products and the equipment that runs such software.

An intriguing example of the power of web-based, user-developed software is Colour Blend,²¹¹ a mobile application for devices running on the Google Android® platform. It identifies the color of whatever is currently in the camera preview, displaying the color name as well as the

²¹¹ Colour Blend was developed by Antony Tran, a software engineer, currently working in Japan (<http://antonyt.com/colour-blend/>)

RGB value. Colour Blend offers a useful tool for individuals suffering from a number of forms of CVDs.

Color Perception

Despite all the mathematical certainty inherent in the physics of light and the somewhat straightforward (although complex) anatomy and physiology of color vision, color is ultimately a strongly subjective perception (Adobe Systems, 2000; Goldstein & Brockmole, 2016). No two people actually "see" the same color because the factors affecting color perception differ from situation to situation and from person to person. To paraphrase a well-known adage, "*Color* is in the eye of the beholder."

The perception of color is a complex process involving both retinal and occipital visual cortical activity. The Young-Helmholtz trichromatic theory (Young, 1802), while unable to explain certain color phenomena (e.g., color constancy, colored shadows, and some color after-images), does explain most of the observed facts about color vision, including most CVDs (International Civil Aviation Organization, 2012).

Color perception begins with the light emanating or reflecting from an object (e.g., a ripe lemon). Physics explains the yellow color of the lemon as a result of the spectral absorption and reflectance properties of the lemon when viewed under a white (broadband) light source. However, such an explanation is flawed, or at least, simplistic (Dvorine, 1971). As early as two centuries ago, the French mathematician Gaspard Monge (1789) had suggested "...that the judgements that we hold about the colours of objects seem not to depend uniquely on the absolute nature of the rays of light that paint the picture of objects on the retina; our judgements can be changed by the surroundings, and it is probable that we are influenced more by the ratio of some of the properties of the light rays than by the properties themselves, considered in an absolute manner" (Mollon, 1995; Shevell, 2003).

A complete understanding of color perception has been slow in coming and has not yet fully been achieved. While many color perception phenomena (e.g., simultaneous and successive color contrast, color constancy, and complementary afterimage), have been studied in detail, how colors are perceived by the human visual system continues to present more questions than answers. Understanding color perception might be an easier task if it did not have so many confounds, e.g., bias, emotional state, and (very importantly) luminance perception. The interaction between color and luminance information in visual processing is well known (Vergeer, Anstis, & van Lier, 2015). From artificially simple to complex naturally occurring scenes, luminance and color signals interact to determine an object's perceived shape and surface appearance (Kanga and Shevell, 2008). Much of this interaction is based on the visual system's processing of luminance contrast boundaries (Kanga and Shevell, 2008). Vergeer, Anstis, & van Lier (2015) have demonstrated a single colored stimulus can produce different percepts depending on the shapes and positions of superimposed thin black contours. Their data suggest spatial averaging of colors occurs between contours. Additional studies have demonstrated similar effects related to spatial averaging of "real" colors (Anstis, Rogers, & Henry, 1978; Anstis, van Lier, & Vergeer, 2012) and spatial spreading of afterimage colors (van Lier, Vergeer,

& Anstis, 2009). Consequently, perceived color can depend on the presence of other colors and on colors viewed immediately before (Hurlbert, 2002) (see Background (surround) section).

In reality, the perceived color of objects can be affected by a multitude of factors, which include: viewing angle, color of the background (surround), object and background surface textures, size or viewing distance (subtended angle), shape, type of illuminant(s), and illumination level.²¹² These, and other factors, generally are placed in three categories: physiological, physical (or environmental), and psychological.

Physiological factors.

Viewing angle and object size are examples of physiological causes of differences in perceived color. If an object is viewed from an extreme angle, the reflected light rays will fall on the periphery of the retina, and the object will be perceived as grayish in color (Dvorine, 1957). This is a result of the distribution of cones within the retina (Figure 126. p. 182) (see *Anatomy and Physiology of Color Vision* section). The central visual field is color-sensitive, has high acuity vision, and functions at high levels of illumination, whereas the periphery is relatively color insensitive, has poor visual acuity, and is more sensitive at low levels of illumination. Consequently, color perception may be expected to vary across the visual field, being best in the foveal region and declining in the periphery.

Investigations of color vision in the peripheral retina date as far back as the 1890s and continue today (Hess, 1889; Baird, 1905; Lythgoe, 1931; Weale, 1953; Moreland & Cruz, 1958; Mullen & Kingdom, 1996; Mukhamadeev, 2014). Until recently, it was generally accepted color vision in the peripheral field was less developed than color vision in the central field. Most estimates placed a limit of trichromatic vision at no more than 30 degrees from central fixation with no color perception beyond approximately 50 degrees of eccentricity. Most recent studies still support a loss of color sensitivity in the periphery (e.g., Newton & Eskew, 2003), with sensitivity to red-green color variations declining more steeply toward the periphery than sensitivity to blue-yellow colors (Hansen, Pracejus, & Gegenfurtner, 2009). This decline is believed to be due to the unselective or random contribution of L- and M-cones to the receptive field surround (Hansen, Pracejus, & Gegenfurtner, 2009). Some studies report small-stimuli color vision becomes dichromatic (lack L-M cone opponency) at angles of 25-30 degrees and is totally absent beyond 40 degrees (Moreland, 1972). However, more recent studies found stimulus size to be a critical factor, and given sufficient size, fovea-like color vision can be present out to at least 45 degrees (Abramov, Gordan, & Chan, 1991; Buck, Knight, Fowler, & Hunt, 1998).

Object size (or area size) can affect color perception. For a large area, such as a painted wall, colors tend to appear brighter and more vivid than they would if covering smaller areas. This is referred to as the *area effect* (Lee, Kim, Yim, & Lee, 2002) and is a frustration to many persons selecting wall paint from small paint swatches. As the size of an object decreases (smaller subtended angles at the eye), the ability to perceive color is reduced and in the limiting case may disappear altogether. For an object to appear spatially extended (and have a color appearance) rather than point-like, light from it must fall on two or more adjacent cones – the

²¹² Usually, a combination of these factors defines the viewing conditions.

photoreceptors in the retina that produce color vision. Under perfect conditions, an object must subtend an angle of at least 1 arcminute along at least one axis perpendicular to the line of sight. This defines the lower limit of detection visual acuity.²¹³ In the central fovea, the density is approximately 150,000 cones/square millimeter (mm²). Assuming a hexagonal packing of cones, the distance between cone centers can be approximated to about 0.003 mm on the retina. This corresponds to a visual angle of 0.013 degree (0.78 arcminute) between cone centers (Montag, 2007).

The ability to discern *small* color differences also is easier when the areas to be discriminated are large, contiguous (share an edge near the viewed point), and viewed simultaneously (National Aeronautics and Space Administration, 2004). As the viewed areas decrease in size or are separated from each other, discrimination becomes more difficult if not impossible. Color discrimination is greatest when a sharp edge separates the colors to be discriminated, e.g., between a symbol and a uniform background color. When a smooth gradient separates two color areas, the smallest detectable difference in color is larger (National Aeronautics and Space Administration Ames Research Center, 2008). This could have a performance impact for the symbols and alphanumeric characters used in displays.

Viewing an object from different angles can make its color appear brighter or darker, particularly with translucent, pearlescent, and metallic pigments. In metallic paint, for example, metallic flakes are spaced throughout the coating, acting as microscopic mirrors. When viewed at a certain angle, the color will appear lighter (Amookhta, Kandib, & Mahdavian, 2014).

Other differences in color perception due to physiological factors have been discussed in the *Anatomy and Physiology of Color Vision* section and are the effects of CVDs resulting from differences in retinal physiology, primarily related to an absence of one or more cone photopigments, or genetic abnormalities causing differences in the cone absorption spectra (Purves et al., 2012). In a classic example involving a kaleidoscopic array of colors at a fruit stand, an individual with a typical red-green deficiency (deuteranope) would be unable to perceive the various color indications of ripeness, e.g., the yellow of a ripe lemon (Figure 139).



Figure 139. An array of fruit has perceived by an individual with normal color vision (left) and with a red-green deficiency (right).

²¹³ Detection requires only the perception of the presence or absence of a spot or line element, not the discrimination of target detail. The Landolt C and the Illiterate E are common detection targets; the task required is to detect the location of the gap. Recognition, what usually is tested in a clinical visual acuity measurement using a Snellen (1862) acuity chart, requires that the target be identified or named; this requires the identification of letters of the alphabet.

Physical factors.

Physical factors capable of affecting color perception include properties associated with the illuminating source(s) (e.g., type, intensity, and spectral content) and of the object and its surrounds (i.e., surface texture, shape, and color of the background against which the object is viewed) and those.

Illumination.

The level of illumination under which color(s) are viewed strongly influences color identification and discrimination ...two very important color tasks when colors are used for grouping and labeling. By definition, the colors of two distinct areas are discriminable if the viewer can tell that they are two different colors; a color is identifiable if the viewer can recognize which color it is (and, usually, assign a name).

Small color differences can be distinguished when the areas are large, immediately adjacent to each other (share an edge near the viewed point), and displayed at the same time (Arend, Logan, & Havin, 2010). These conditions occur, for example, in visualization of quantized continuous data as in maps of weather, temperatures, pressures or terrain. Larger color differences are required whenever conditions deviate from optimal viewing situations.

Bright sunlight, typically cited at 60,000 to 70,000 lux (5,574 to 6,503 fc) can interfere with the readability and color identification of flight deck displays, switches and indicators. The worst effect of bright sunlight is the reduction of display contrast resulting from adding the bright sun illumination to both the display information and the background (the ratio of which defines the contrast). For the relatively low levels of lighting used on flight decks, if a display were subjected to a 60,000-lux illumination, the contrast ratio would be approximately 1-to-1, with virtually no differentiation between a light source and its background. High ambient lighting conditions also cause the Abney effect, in which (except for yellow and some blues) adding large amounts of white light causes a shift in the perceived hue and can result in a desaturation of color (Prasad, 2002).

Color discrimination is best at moderate (photopic) levels of illumination. At very high levels (glare), color saturation appears as decreased; at very low levels of illumination (approaching mesopic levels), discrimination may deteriorate significantly for individuals with either red-green and blue-yellow deficiencies (Kudo, Smith, & Pokorny, 1993; National Research Council, 1981). At scotopic levels, rods dominate visual processing, and color discrimination is no longer present (see *Photopic, mesopic, and scotopic vision* section).

The type of illumination (i.e., the spectral distribution of the illuminating source) also can have an effect on color appearance. For non-luminous sources, the color appearance of an object or scene is determined by its reflectance spectrum convolved with the spectral distribution of the illuminating source. Figure 140 (left) shows surface reflectance spectra of several common objects; Figure 140 (right) shows the spectral distributions of sunlight and a tungsten bulb, two typical broadband sources (see also Figure 6, p. 19). For any illuminating source containing energy at all of the wavelengths present in the reflectance distribution, the color appearance of an

object will not change with illuminants. However, if the illuminating source is not broadband (e.g., come gas discharge sources [Figure 7, p. 21] with extreme cases being monochromatic sources such as LEDs and lasers [Figure 8, p. 22]), the color appearance can be drastically altered, causing the object to appear unnatural (see *Color rendering* section).

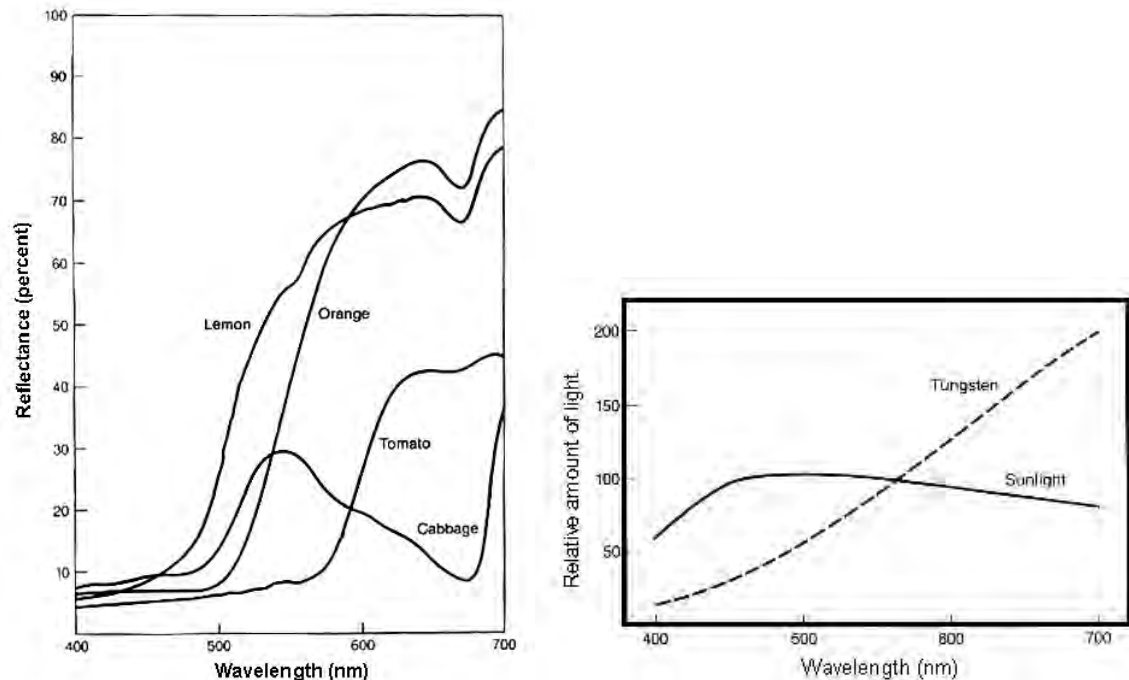


Figure 140. Spectral surface reflectances of common objects (left) and two broadband sources (right) (Source: University of Washington).

Nevertheless, this altered appearance is not certain when the illuminating spectral distribution is only minor. This leads to a paradox of human color vision – a phenomena known as *color constancy*. To reiterate, from the perspective of physics, the color signal (information) reflected from an object is defined by the final SPD reaching the eye; and this depends on the object’s reflective spectral properties and the type of illumination. However, in reality, color perception can be reasonably independent of the spectral composition of the illumination; the exceptions being the monochromatic examples listed above and obviously in total darkness or at extreme intensities. Well known objects, e.g., a favorite sweater, will appear the same under sunlight, incandescent tungsten, or fluorescent lighting. The objects in a room in late evening illuminated by the yellowish light of tungsten-filament lightbulbs will appear to maintain the same respective color balance as during midday when viewed by sunlight entering the room via windows. The human visual system seems to maintain a dynamic “white balance” (Ebner, 2007).

A number of theories, or models, have been developed to explain color constancy (Land, 1964; Jameson & Hurvich, 1989; Fairchild, 1998; Kraft & Brainard, 1999; Rutherford & Brainard, 2002; McCann, 2004; Brainard & Radonjic, 2014). The phenomenon works only if the incident illumination contains a range of wavelengths. The eye’s three types of cones sense different but overlapping ranges of wavelengths of light reflected from objects in the room. In a theory first suggested by H. Helmholtz, from these responses, the visual system attempts to

determine the approximate composition of the illuminating light. This illumination is then discounted or “corrected” in order to obtain the object's “true color” (McCann, 2005). This corrected reflectance essentially determines the perceived color.

Color constancy is maintained under most conditions but not all. It remains to be understood how it comes about, and why it sometimes fails. Color constancy has been known for quite some time. French scientist Gaspard Monge in 1789, German physician and physicist Hermann von Helmholtz in 1860, German physiologist Ewald Hering in 1920, and American inventor Edwin Land in 1971 have all investigated this phenomenon (Foster, 2011). German-born Swedish psychologist David Katz is credited with developing the basic methodology of studying color constancy and is best known for his extensive experimental work in the study of lightness and color constancy (Katz, 1911, 1935; Gilchrist, 2006). The topic continues to be one of interest to vision psychologists.

Color constancy serves to emphasize the point color is not simply recorded by the eye but is a perception. An historic demonstration of this was provided by E. Land in 1958 when he showed how it was possible to evoke the perception of colors in everyday scenes when light of the prevalent wavelengths were actually absent from the image focused on the retina (Land, 1959a,b). Land is best known for his innovations in film photography, e.g., instant film and the Polaroid²¹⁴ camera. So, it is ironic that photographic film does not exhibit color constancy but instead captures the differences in types of illumination.

Surface texture.

Color perception also is impacted by a more trivial but still interesting physical factor – surface texture (Arend, 1994, 2001). Surface texture, or surface topography, is the nature of a surface as defined by the three characteristics of lay, surface roughness, and waviness (Dalton, 2009).²¹⁵ Surface texture is comprised of the small, local deviations of a surface from an ideal plane and is a determining factor in how light is reflected. This consequently may affect color appearance (; Giesel & Gegenfurtner, 2010; Amookhta, Kandib, & Mahdavian, 2014).

It has been shown surface texture, while seemingly a minor characteristic of an object, influences the memory color of objects (Vurro, Ling, & Hurlbert, 2013).²¹⁶ Illumination, surface roughness, and glossiness²¹⁷ also impact the phenomenon of color constancy (Granzier, Vergne, & Gegenfurtner, 2014).

Background (surround).

One of the most studied topics considered to be the effect of a physical factor in color perception is the effect of the color of a background (or surround) has on the perceived color of an object or area viewed (at the same time) against that background (Heinemann, 1955; Dresch &

²¹⁴ Polaroid Corporation, Cambridge, MA.

²¹⁵ *Lay* is the direction of the predominant surface pattern, usually determined by the production method. *Roughness* refers to irregularities in the surface texture that result from the inherent action of the production process. *Waviness* is the component of surface texture upon which roughness is superimposed.

²¹⁶ *Memory color* and *color memory* are frequently interchangeable terms and usage depend on context. Both imply the ability to match colors successively rather than simultaneously (see *Color memory* section).

²¹⁷ *Glossiness* is the surface characteristic of having a well-defined specular reflectance.

Fischer, 2001; Pinna, 2008; Ratnasingam & Anderson, 2017). This effect is known as *simultaneous color contrast*, first investigated by French chemist Michel-Eugene Chevreul (1839, 1855). Its implication is the appearance of a color can change because it is viewed against another (background) color (Foley & Matlin, 2010). Few objects are viewed in isolation. Rather they are surrounded by other colored objects and areas. Work by Ekroll and others have shown individuals perceive colors differently against colored backgrounds as compared to achromatic backgrounds (MacLeod, 2003; Ekroll, 2005; Ekroll & Faul, 2012). Likewise, individuals perceive colors differently against uniform surrounding color fields (Ekroll, Faul, & Niederee, 2004).

In Figure 141 (top), the two red borders are the same color, but the one on the left appears slightly yellowish when surrounded by a light chartreuse background, but slightly bluish when surrounded by bright violet on the right. In Figure 141 (bottom), against the blue background the gray circle takes on a yellowish tint; and against the yellow background, it takes on a bluish tinge (Foley & Matlin, 2010).

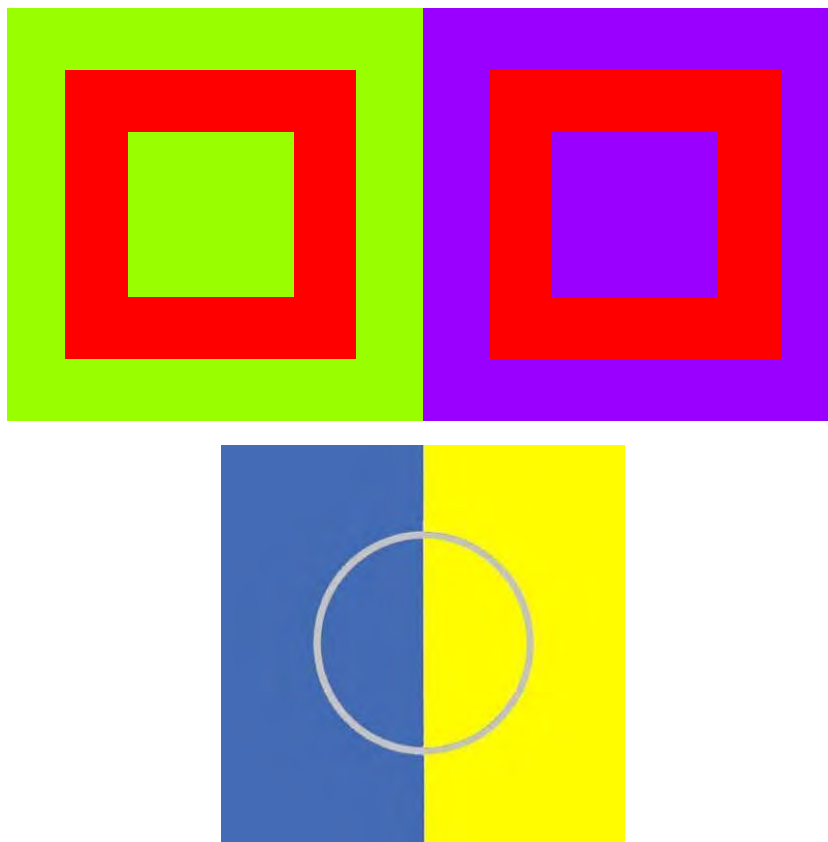


Figure 141. Examples of simultaneous color contrast.

Simultaneous contrast refers to visual effects in which the appearance of a patch of light (the "test field") is affected by other light patches ("inducing fields") that are nearby in space. There is a closely related effect, *successive contrast*, for which the "test field" and "inducing field" are nearby in time, i.e., the effect of a previously-viewed color field on the appearance of a currently-viewed field (Newhall, Burnham, & Clark, 1957). One example of this effect arises

when switching gaze from one hue area to another neutral area. The more recently viewed area will take on an appearance based on the complementary colour of the first viewed area. This effect is stronger if the first hue is more saturated. In Figure 142, if the bright, colored box area on the left is viewed for approximately ten seconds and then the right gray area is viewed, the gray area will present a temporary illusion of an area composed of the "missing" wavelengths. This is an afterimage effect and was discussed (but not claimed) by Hering as evidence for his opponent model of color vision. Successive contrast results from adaptation...not "fatigue"... of the eye. When viewing a blue object, the S-cones are not being "fatigued" any more than they are in viewing a white object – the effect is caused by the increased sensitivity of the other cone types (Briggs, 2007b).



Figure 142. Successive color contrast.

Several characteristics of this phenomenon are (Wyszecki & Stiles, 1982): a) The effect fades after a few seconds; b) The afterimage can be multicolored and preserves the spatial shapes of the inducing field; and c) The afterimage can alter the appearance of both white and colored fields. Most demonstrations of this effect present color images designed to produce strong effects. However, the effects can be strong enough under some conditions to produce misidentification of the labeling color of a symbol.

While previously categorized as a physiological factor based on the angle of light entry into the eye, viewing angle also can be a physical factor related to the angle of an illuminating source with respect to the object being viewing. An aviation example of this was provided by U.S. Army pilots with the 135th Aviation Regiment of the Kansas National Guard who assisted with counterdrug operations in 1993 (Mechels, 1993). While shape, texture, and pattern are useful, they explained color was the first and most obvious visual cue in locating marijuana plants. Marijuana usually appears as a bright emerald-green color, usually with a slight bluish tint. This color can be influenced by growing season and conditions (e.g., wild vs. cultivated growth). They further emphasized flying earlier or later in the day improved color contrast, because of the lower angle of the sun, and color and texture often showed up better from one angle as opposed to another.

Psychological factors.

A third category of factors influencing the perceived color of an object is psychological in origin. Previous discussions have described aspects of color psychology regarding how the perception of color is influenced by age, gender, cultural factors, past experiences (see *Color in Culture and Symbolism* section). Most of that discussion focused on color preference and emotion. Psychologists have long proposed theories that longer wavelength colors (e.g., reds) illicit a feeling of arousal or warm, whereas shorter wavelength colors (e.g., blues) illicit a feeling of relaxation or coolness; these theories have been used in commercial advertising (Goethe, 1810; Nakashian, 1964; Crowley, 1993). Goldstein (1942) summarized these theories by stating certain colors produce systematic physiological reactions evident in emotional experience (e.g., negative arousal), cognitive orientation (e.g., outward focus), and overt action (e.g., forceful behavior). In a review of theoretical and empirical work in the area of color and psychological functioning over the 1990's and 2000s, Elliot (2015) concludes advances in this area "are limited in scope in terms of range of hues, range of color properties, and direction of influence" researched. The review further emphasizes the failure of previous research to exercise proper color stimulus control (i.e., lack of appropriate spectroradiometric equipment for color stimuli assessment and presentation), as well as the failure to recognize that color perception "is not only a function of lightness, chroma, and hue, but also of factors such as viewing distance and angle, amount and type of ambient light, and presence of other colors in the immediate background and general environmental surround." To summarize this last point, it must be realized color is not perceived alone but in combination with other effects in the environment.

Most, if not all, color psychology research has been directed at the impact of color on psychological and emotional responses in the observer. In contrast, literature searches have been unable to identify any studies investigating changes in perceived color due to emotional state.

Shape.

The shape of an object also can be a psychological factor in color perception, based on predetermined biases. This circumstance is based on the concept experience and expectation can influence perception (Niedenthal & Kitayama, 1994; Goldstone, 1995). One conclusion from this work is concepts and categories can influence perception. Experiments show perceived color contrast can be influenced by learned categories (of shapes). In one experiment, Goldstone (1995) found "objects that belonged to categories with redder objects were judged to be 'more red' than identically colored objects belonging to another category." Earlier studies have shown shape context influenced color appearance; an object's color was distorted toward the color suggested by the object's shape or shape category (Bruner, Postman, & Rodrigues, 1951; Harper, 1953). For example, a color patch placed on a banana-shaped figure was matched to a "truer" yellow than the same color on a strawberry-shaped figure.

Effects of color on other perceptions.

So far, the discussion of color perception has been from an external perspective, i.e., how properties of the object, background, and illuminating source affects perceived color. However, another perspective is whether color perception has any effect on other visual perceptions (of

objects), e.g., size, slant depth, and shape (Nefs, 2011). Of these, the most common is effect on size (Gundlach & Macoubrey, 1931). This is a perception influenced by context (Gold, 2014). While size has been presented earlier as a physiological factor in color perception for very small objects (i.e., small subtended angles at the eye), size and color also can interact in the opposite direction; color can influence the perceived size of a shape or object.

The perceived size of an object may be influenced by surrounding color. In Figure 143 (left), both the inside green box on the left and white box on the right are the same size; but, the left green box usually is perceived as being larger. The perceived size of each box is affected by the color surrounding it. Also, in this illusion, the left framed green box captures more attention, making it seem larger. In Figure 143, right, the contrast between the white circle and the green background causes the white circle to appear larger.



Figure 143. Color contrast size illusion.

Cleveland & McGill (1983) reported participants erred in judging the size of colored area in statistical maps. Claessen, Overbeeke, & Smets (1995) found participants in a puzzle task consistently selected larger or smaller pegs to fit a hole when the peg was colored. Tedford, Bergquist, & Flynn (1977) reported rectangles of the same size, saturation, and brightness appeared to have different sizes when colored red-purple, yellow-red, purple-blue, or green (in order of decreasing apparent size). At high saturations, this effect was statistically significant for all color pairs except yellow-red and purple-blue; at low saturations, only the differences between yellow-red and green rectangles were significant. When the hue was held constant and saturation varied, rectangles with higher saturations consistently were judged to be smaller in size than less saturated rectangles. These studies imply color has an influence on size perception, which depending on task and other factors (e.g., luminance) can result in human errors.

While studies are limited, there seems to be little evidence that perceived color can affect slant and shape perception. Troscianko, Montagon, Le Clerc, Malbert, & Chanteau (1991) found isoluminant chromatic gradients from red to green did not affect the perceived slant of a surface. Neither has hue been found to have a measureable effect on perceived shape (Claessen, 1996). However, color does seem to have an effect on binocular depth perception for certain foreground-background color combinations. Known as chromostereopsis,²¹⁸ this effect is most pronounced when a red object is viewed against a blue background (Figure 144, top), where the red object can appear to be in front of the blue background.²¹⁹

²¹⁸ *Chromostereopsis* is a visual illusion whereby the impression of depth is conveyed in 2D color images, usually of red-blue or red-green colors, but can also be perceived with red-gray or blue-gray images. Such illusions have been reported for over a century and have been attributed to chromatic aberration.

²¹⁹ For some people the effect is reversed, with blue standing out and red receding.

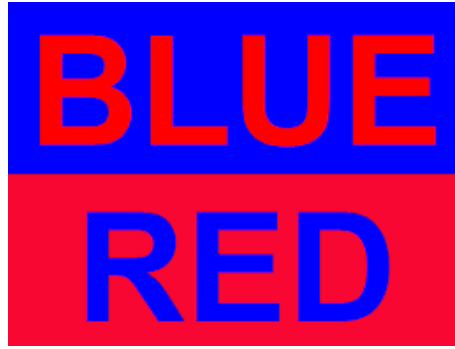


Figure 144. Chromostereopsis, a color effect on depth perception.

Color illusions.

As color itself often is portrayed as a perceptual illusion, it is most appropriate to close the discussion of color perception with a topic that incorporates many of the concepts presented above – color illusions. A somewhat formal definition of any visual illusion is of a perception or interpretation of an image that differs from objective reality (i.e., a misperception or misinterpretation) resulting from the function of the visual system. Color illusions are a subset of visual illusions where color plays a role in the misinterpretation. In many of these illusions, the visual system is tricked into an incorrect interpretation of color.

Many of these illusions can be characterized as follows (Rheingans & Landreth, 2013):

- The perceived hue of a color may be influenced by its saturation.
- The perceived saturation of a color may be influenced by its hue.
- The perceived depth of an object may be influenced by its color.
- The perceived color of an object may be influenced by the color of surrounding objects.

An amusing, but frustrating, color illusion is the color reading illusion, also known as the Stroop effect, named after American psychologist J. Ridley Stroop (1935) who discovered the phenomenon in the 1930s (Dyer, 1973). In Figure 145, two “reading” tests are presented demonstrating a spatially-driven interference of conflicting color stimuli (i.e., reading of the word and the color of the word). The task is to read through the list of colors, but instead of reading the words, speak the color of each word. For the top list, the task should be easier than for the bottom list, where there is a conflict between what is read and what is perceived. It also has been suggested the latter task is more difficult because it requires both hemispheres of the brain to work together (Chudler, 2015).

Color memory.

The ability to remember specific colors is poor (Burnham & Clark, 1955; Hamwi & Landis, 1955). But, good color memory is not the ability to remember the color of the tie your boss was wearing at the last meeting – at least, not unless the tie was being scrutinized for the purpose of determining his/her favorite color for a future gift. More precisely, color memory refers to a task that requires color matching, not by comparing two colors simultaneously side-

by-side but instead by comparing two colors, only one of which is immediately viewable and the other having been viewed in the past (even very recently) (Newhall, Burnham, & Clark, 1857). This sometimes is known as “successive color matching” (de Fez, Capilla, Luque, Pérez-Carpinell, & del Pozo, 2001). The differentiation here is between color matching where both of the objects (colors) are present (perception) and where one is absent (memory).



Figure 145. The Stroop effect.

Consider these commonplace color memory situations:

- Picking out a paint color at a local building supply store to match a bedroom wall using paint sample chips (Figure 146)
- Selecting a fabric from shop swatches to make a throw pillow that will match existing living-room draperies



Figure 146. Paint sample color chips.

In each of these situations, a color match is being based on a visual working memory of a color. The difficulty in correctly using this memory is not well understood, but may be explained by a model where attempts to color match from working memory are found to be significantly directed away from category boundaries that might define specific colors and toward category centers. This can occur even without a lengthy memory delay (Bae, Olkkonen, Allred & Flombaum, 2015). In the bedroom wall example above, while individuals are highly sensitive to subtle differences in hues and shades, when stored in memory, many specific colors, e.g.,

aquamarine, azure, aqua, baby-blue, are each “stored” as *blue*. However, in situations where a specific color is associated with a very familiar object (e.g., a favorite sweater) or a color with a strong emotional connection (e.g., school color), an established visual memory seems to be “better” stored and is more dependable (Bartleson, 1960; Pérez-Carpinell, de Fez, Baldovi, & Soriano, 1998).

In general, studies show color memories tend to be significantly different from the original perceptions, with changes in both dominant wavelength and color saturation (Katz, 1935; de Fez, Capilla, Luque, Pérez-Carpinell, & del Pozo, 2001). While a number of studies have found certain colors have characteristic differences making them more difficult or easier to remember than others, there has been only a general agreement in the findings (Epps & Kaya, 2004). Two classic studies found particular wavelengths of green and red were hard to reproduce and difficult to recognize repeatedly (Collins, 1931; Hamwi & Landis, 1955). A more recent study found the most accurately remembered colors were violets, green-blues, and yellow-oranges (Nilsson & Nelson, 1981). However, another study showed long and medium wavelengths (greens and reds) were remembered more accurately than shorter wavelengths (blues) (Jin & Shevell, 1996).

Color Vision Tests and Standards.

With vision being the primary sense via how humans interact with the environment, it seems reasonable to test visual function, including color vision, with some regularity. While many individuals undergo yearly visual exams, color vision testing often is not included unless there is suspected retinal or optic nerve disease or damage, a family history of CVDs, or the individual specifically voices a color vision concern (Bailey, 1980; Erba et al., 1998). Without routine screening, many individuals with mild color deficiencies may be unaware of their deficiencies, missing out on much of the color variations (and information) around them (Blake, 2004; Cole & Lian, 2006) and facing many daily situations that could pose real hazards, e.g., difficulty in detecting traffic lights against complex backgrounds and misidentifying potentially dangerous plants, snakes, and insects (Cole, 1972; Steward & Cole, 1989; Langley, 2015).

A need for color vision testing and, hence, the development of specialized color vision tests, serve two major purposes: clinical screening for hereditary and acquired CVDs, and evaluation for occupational color vision requirements (French, Rose, Thompson, & Cornell, 2008).

It seems reasonable full clinical vision screenings would be important to ensure candidates for certain occupations, including pilot training, have good visual function, including color vision. Additionally important would be the maintaining of regular, periodic screenings to ensure color vision has not been compromised.

There is an additional concern, one which addresses the issue of color vision testing for work-related purposes, i.e., where specific color vision tasks are a requirement for a given occupation. Of great interest here would be aviation-related occupations. While dependent on workplace and hiring specifics, a large number of occupations today do have such requirements for color vision, e.g., railway, trucking, manufacturing, medical, advertising, marine, and the

military. The identification of color aptitude can be essential for vocational guidance in occupations or professions requiring color judgments or unique color-related skills (National Research Council, 1981).

A number of occupations where personal and/or public safety is a concern have established color standards but may admit individuals with mild CVDs. These include (Pease, 2006):

- Military
- Aviation
- Electrical and telecommunications
- Maritime
- Railroad
- Commercial transportation (e.g., truck, bus, taxi)

There also are a host of occupations where normal color vision is desirable, as performance may be compromised by the presence of moderate to severe CVDs. These include (Pease, 2006):

- Artist
- Botanist
- Butcher
- Firefighters
- Florist
- Gemologist
- Interior designer
- Medical sciences (e.g., dentist, nurse, optometrist, pharmacist, physician, surgeon, veterinarian)
- Photographer
- Theater, film, and television

As is discussed below, most of the occupational requirements for color vision testing and their obligatory standards arose from century-old safety concerns, e.g., railway and other transportation accidents, not from visual performance concerns per se. And, in recent years, a number of questions have been raised about the need, accuracy, and legality (e.g., workplace antidiscrimination laws) of these requirements (Birch & Rodriguez-Carmona, 2014).

A limited number of few studies have been conducted to empirically validate the color vision standards within the USAF (Tredici, Mims, & Culver, 1972) and industry (Good, Weaver, & Augsburger, 1996), while the color vision standard for air traffic controllers (ATCs) has been studied extensively (Mertens, 1990; Mertens & Milburn, 1992, 1996; Milburn, 2004). The majority of vision standards for various occupations have not originated from such empirical testing but instead from expert opinion or the standards previously developed for other occupations (Beard, Hisle, & Ahumada, 2002). There is an obvious needs for a reevaluation of

such standards, especially for military occupations (see Issue #3 in *New and Continuing Color Issues and Future Research* section).

To explore the issue of occupational color vision testing, first the importance of testing color vision, both in general and with respect to occupational requirements, will be discussed; next, a list of the many available color vision tests is provided (including a brief historical perspective), and the more common tests are described and evaluated with a focus on their ability to predict aircrew flight performance of which color tasks are an important component; and lastly, the development of standards for measured performance on these color vision tests will be discussed. This latter discussion will include a list of current military standards and the recent (and not so recent) call for a reexamination of their continuing validity.

Importance of testing color vision.

To ask the question “Why does color vision testing really matter?” is to suggest excellent, good, poor, or even no color vision makes no difference in the day-to-day life of individuals. For most individuals, color vision is as routine function as breathing; it is not given a second thought. Even within the aviation community, color vision is taken for granted. In a posting on an unofficial U.S. Naval aviation community forum (Airwarrior.com, 2013), a pilot says “Not to sound wildly uneducated about color vision but isn't color vision... color vision? You either got it or you don't?” This is a perspective not limited to aviation.

It is known color vision is an evolved capability (Nathans, Thomas, & Hogness, 1986; Bowmaker, 2008; Jacobs, 2009) and a process humans use to extract additional information from a scene based on the spectral (wavelength) composition of the visual stimuli (Nathans, 1999). This ability to see colors is not universal across the animal kingdom but is prevalent in many primates, including humans (Gerl & Morris, 2008; Jacobs, 2008; Bryk, 2011). (See *Anatomy and Physiology of Color Vision* section.)

An awareness of degraded or a total absence of color vision appears to be lacking in the ancient world, a fact most likely due to early Greek theories²²⁰ culminating in Aristotle's theory, in which color was based on the interaction of stimulus brightness and ambient light level (Benson, 2000). While Kepler (1571-1630), Descartes (1596-1650), Huygens (1629-1695), and Newton (1643-1727) studied color phenomena from a physics and optics perspective, it would not be until the end of the 18th century before English chemist and physicist John Dalton, renowned for his atomic theory, would bring “the vision of colours” as an important subject of scientific study and of interest to mainstream literature (at least in Western civilization) (Hess, Nordby, & Sharp, 1990). Dalton (1798) provided one of the first accounts of “colour blindness”²²¹ based on his personal experiences. Both he and his brother were color deficient, causing Dalton to conclude the condition is hereditary (Johndalton.org, 2017). In 1995, a DNA analysis of tissue from one of Dalton's eyes confirmed he lacked the M-cone type of photoreceptor, the one more sensitive to green light (deuteranopia) (Hunt, Dulai, Bowmaker, &

²²⁰ To include Alkmaion of Cretona (a Pythagorean physician), Empedokles, Demokritos, and Plato (Benson, 2000).

²²¹ The terms “colour blindness” or “color blindness” are frequently used incorrectly. Actual total color blindness (achromatopsia), where individuals see only shades of gray, is very uncommon, occurring in less than one in 30,000 people. The term *monochromacy*, the total lack of the photopigments in cones, which are responsible for color vision, also may be encountered.

Mollon, 1995). The word "Daltonism" became a common term for color blindness, derived from "daltonien," the French word for "colour blind."

In what may be one of the earliest documentations of an individual who possessed no color vision, D. Turberville, writing in *The Philosophical Transactions of the Royal Society* in 1684, describes a 21-year old woman who had good vision with the exception of lacking the ability to see colors except for black and white (Hess, Nordby, & Sharp, 1990). It was reported her lack of color vision had followed an (unidentified) illness.

The next documented Western European case was a century later, when J. Huddart (1777) describes a resident of Mayport, Cumberland, England, who could discern easily the form and size of objects, could distinguish between black and white, but could not distinguish colors. This individual claimed to have first become aware of his difference in vision at an early age. He had observed other children could easily find ripe, red cherries on trees at a greater distance than he, although he could see other objects at greater distances than they could, unless the objects were enveloped in other things, e.g., cherries among tree leaves.

However, since neither John Dalton's eminence nor the other incidences were apparent occupational concerns, they elicited no recognized need for formalized color vision testing; it would take an accident of sensational proportion to generate such a change. Considered to be the origin of occupational color vision screening is the fatal railroad accident that occurred in Sweden on the night of 14-15 November 1875 (Mollon & Cavonius, 2012). Known as the Lagerlunda accident, after the closest city, Lagerlunda, Sweden, it involved two of the most high-status express passenger trains in Sweden. One was travelling southbound, the other northbound. Critical events associated with the sequence of miscommunications and human error (including signal colors) set the stage for the accident and resulted in nine deaths, including one of the engineers, both firemen, and one oiler (Mollon & Cavonius, 2012).

In the investigation that followed, the noted Swedish physician and physiologist, Frithiof Holmgren, suggested the engineer of the northbound express and/or his oiler had failed to correctly interpret the color of signals because they were "color blind." As neither survived the accident, this fact could not be confirmed. Nevertheless, the intense publicity of the trial and unsubstantiated claims both during and after the trial resulted in the conclusion "color blindness" was the cause of the accident. This conclusion almost single-handedly brought the introduction of color vision testing to European and North American railroads and opened the way to the establishment of color vision testing for a host of occupations, based on both safety and job performance (Mollon & Cavonius, 2012).

Much more recently within the railroad industry, the issue of occupational CVD requirements gathered public attention in two U.S. accidents (Wright et al., 2016). In a 1996 New Jersey railroad collision that killed 3, injured 158, and caused \$3.3M in damage, the train engineer failed to report a medical condition that precipitated an acquired CVD. This failure was compounded by the medical examiner not following proper color vision testing protocol. As a result, the condition went undiagnosed. Subsequently, an event occurred where the engineer misinterpreted a red stop signal, failed to yield, and struck a commuter train (National Transportation Safety Board [NTSB], 1997). Defective color vision was similarly cited as a contributing factor in a railroad collision in Oklahoma in 2012 (NTSB, 2013). The engineer

suffered from an acquired color vision loss as well as reduced visual acuity secondary to multiple ophthalmic pathologies including glaucoma, cataracts, cystoid macular edema, and epi-retinal membranes. Despite his medical complaints, his difficulty in seeing signals, and not meeting either color vision or visual acuity standards, the engineer maintained his medical certification. The NTSB determined the probable cause of the accident to be the engineer's inability to see and correctly interpret a colored signal. This event resulted in 3 fatalities and \$14.8M in damage.

Occupational screenings would detect both hereditary and acquired color deficiencies. Approximately 15% of the general population has an acquired color defect, to include such common causes as cataract yellowing, diseases resulting in loss of foveal function, optic nerve disease, neurological diseases and injuries, and glaucoma (Pacheco-Cutilla, Edgar, & Sahraie, 1999; Ivan, 2013; Simunovic, 2016). In addition, it is known a large multitude of commonly available legal and illegal drugs can affect color vision (Pitts & Kleinstein, 1993; Gupta, Agarwal, & Srivastava, 2014). The literature lists over 300 drugs with a known impact on color vision (Abel, 2014); these include many common prescription (e.g., treatments for erectile dysfunction, tuberculosis, multiple sclerosis, and heart conditions) and over-the-counter medications (e.g., ibuprofen, aspirin, and some herbs). Fortunately, most drug-induced changes in color vision are temporary and dissipate when use is terminated.

When discussing operational color vision requirements, it is generally accepted pilots, especially military pilots, have met a set of high standards for visual performance, including color vision (see *Vision standards* section.) In practice, every pilot does not have “perfect” color vision. In civilian aviation, while the FAA requires applicants to meet its color vision requirements, it does allow the aviation medical examiner (AME) to issue an otherwise qualified applicant a medical certificate with the limitation “Not valid for night flying or color signal control” (FAA, 2014a).

As for military pilots, a 1995 U.S. Army report found many U.S Army aviator training applicants being disqualified routinely from flight training due to CVD and the presence of such deficiencies in rated aviators²²² for the observed period of calendar years 1982 to 1992 to be rare, with an incidence of approximately one new case per 10,000 aviators per year. However, there were a number of incidents of exception to policy for known CVDs, development of acquired CVDs, and aviation medicine clinic screening program failures due to poor methods or deception by applicants and conspirators (Mason, Shannon, & Slattery, 1985).

CVDs may affect the performance of all military personnel, not just aviators. A CVD is a common disqualifying factor for a number of military operational specialties (MOSs) in the U.S. Army. For many MOSs, the ability to accurately perceive colors is critical to mission success. Emerging tactical displays use color coding as a friend/foe discriminator, which stresses the importance of normal color discrimination. As new and emerging display technologies find use in a growing number of applications, color continues to be the visual attribute used to encode a spectrum of mission critical information. These new display technologies demand personnel color vision standards be task relevant. This requirement is more evident for military pilots due

²²² For the U.S. Army, a *rated aviator* is an individual who has successfully completed a prescribed aviation-related training or equivalent experience. Current U.S. Army aeronautical ratings include Army aviator, senior Army aviator, and master Army aviator. As an example, for the *Army aviator* rating, an individual must be a graduate of the Initial Entry Rotary Wing (IERW) Course or Flight School XXI (FSXXI) and medically qualified class II or have related service in another U.S. Military Service. (Department of the Army, 2010)

to the advanced, color-rich, modern aircraft cockpit. With the advent of the multicolored glass cockpit, normal color vision is deemed essential by many pilots and experts. These systems have not been designed with color defective individuals in mind, nor do they currently permit reconfiguration to accommodate individuals with CVDs. The color vision needed by pilots is changing from a limited presentation of colors (mainly red, green, and white) outside the cockpit for short periods of time to more color-demanding displays inside the cabin, which are used for longer periods of time. While pilots in the past used colors primarily for safety and navigation, with newer displays, pilots must interpret complex, differently-colored symbols and colors used for multiple mission-related tasks. Color vision is required for air-to-ground operations (e.g., map reading, visual target confirmation, smoke marker detection) as well as for air-to-air operations (e.g., visual identification of hostile aircraft) (Bailey, 1965a; Cole, Lian, & Lakkis, 2007).

Degraded performance of color defectives is well established in the scientific literature, characterized by increased error rates, time delays, and reduced effective range. Performance can be degraded further in reduced ambient illumination associated with night flight operations (Mertens & Milburn 1996). A color defective pilot may face challenges in complex color-based environments that place more stress in the visual system and decrease the ability to perform color-related duties (e.g., must be closer to target to discriminate it based on color information; takes longer to interpret color-based information). It is well documented pilots having even mild CVDs have experienced problems with the EFIS and other color cockpit displays (Cole & MacDonald, 1988; Mahon & Jacobs, 1994; Cole, 2004). Additional demands on the visual system affecting color vision include: rapidly fluctuating ambient illumination, glare (direct or reflected), afterimages, and use of selective waveband filters and laser eye protection. Protective devices and performance-enhancing optical systems can degrade color perception in many unpredictable ways (see *Special Color Issues in U.S. Army Aviation* section) (Delpero, O'Neill, Casson, & Hovis, 2005).

There is a need for a rapid clinical color vision test that can effectively identify individuals with CVDs in the U.S. Army (and the rest of the tri-service community). The color vision screening tests currently used by the U.S. Army are problematic for various reasons. First, they provide only a “pass-fail” determination without quantifying the severity of the CVD and frequently incorrectly identify pilot candidates as having normal color vision when they actually are color deficient. Second, a number of the tests historically used as the primary method of color vision screening in the U.S. Army are no longer commercially available. Third, some tests do not screen for acquired tritan (blue-yellow) CVDs, congenital or acquired. Fourth, current tests are easily affected by variation in testing conditions (e.g., illumination, administration procedure, administer encouragement, and by applicant deception to defeat the test (see *Testing issues* and Issue #4 in *New and Continuing Color Issues and Future Research* sections).

History of color vision testing.

The first commercially available color vision test usually is cited as the Holmgren (1877) Wool Test developed for examining train engineers (French, Rose, Thompson, & Cornell, 2008). It consisted of 75 different colored small wool strands to be matched to three larger standard skeins, colored red, green, and purple (Figure 147, left). The large skeins served as test colors,

the small strands as comparison or matching colors. The skeins were placed in a heap, and one standard skein was selected. The observer was asked to select strands from the heap most nearly matching in color the test skein. There was no exact match, but similarly colored skeins (i.e., skeins of lighter or darker shades of the same color) could be selected. The procedure was repeated for each standard skein. There was no identification of the skeins. An instruction sheet accompanied the test, but there was no scoring sheet or scoring instructions. The examiner was directed to look for hesitation and for the selection of dissimilarly colored skeins (e.g., for the red test skein, the selection of other colors, such as green, blue, brown, or yellow strands). Because the colors of the standard skeins were based on the incorrect color vision model by Helmholtz of three types of color defects (i.e., red-blindness, green-blindness, and violet-blindness), the accuracy of the Holmgren test was questionable (Birch & Patel, 1995). The skeins varied considerably from set to set (National Research Council, 1981); no calibration was required; and an illuminant was not specified. This test is now considered an historical oddity and is not recommended as a suitable screening test. However, the wool test was still available from the U.S. Naval Medical Supply Depot well into the 1940s (U.S. Naval Submarine Base Medical Research Laboratory, 1942), and at least until the mid-1960s, it was listed in the inventory of color tests at the USAARL (Bailey, 1965b).



Figure 147. (Source: Science Museum, London).

A number of variations of this type of test were developed (e.g., Thompson & Weiland [1897], Oliver [1902], and Abney [1906]). The best known of these is the Edridge-Green Colour Bead Test (Edridge-Green, 1891, 1920). Frederick William Edridge-Green (1863-1953) was a British physician and surgeon who took a particular interest in color perception. His test consists of a number of colored beads housed in a tray in the base of a wooden box (Figure 147, middle). The top tray of the box has four holes labeled red, yellow, green, and blue. The test subject is directed to pick out from the bottom tray all beads that are, for example, *red*, keeping as nearly as possible to the exact hue but selecting those lighter or darker of the same color and to drop them one by one into the compartment hole labeled *red*. This process is repeated for the remaining colors. Another variation is the Donders Wool Rolls Test (Figure 147, right) developed in 1879 by the Dutch ophthalmologist F. C. Donders (1818-1889) at the University of Utrecht. While his test also was based on matching, Donders strongly advocated naming of colors be rigidly required in color vision testing (Scripture, 1899).

Color vision testing actually can be traced back to the late 17th century to where Turberville (1684) employed a method to test color vision by comparing the individual's color naming of everyday objects with that of other normal persons (considered to have normal color vision). It would be a century later until Dalton (1798) would document color perceptions of his own, his brother, and 20 other persons, based on the naming of the colors of various ribbons. He was followed by August Seebeck (1837), who used a set of more than 300 colored papers he asked people to match or find closely related colors. This type of color vision test, which relies on matching, was an improvement over previous naming tests, the responses to which could differ greatly between persons (Colblinder, 2010). Holmgren adopted this matching approach in his 1877 test using skeins of wool.

What would become the basis for the most common type of color vision test was first introduced by J. Stilling of Strasburg (Stilling, 1879, 1910; Ryan et al., 2012). This test, developed in 1876 and became widely available in 1883, relied on one or more printed plates presenting a figure composed of colored dots against a background of differently colored dots (Figure 148, left). This plate, known as a pseudoisochromatic plate (PIP), later would be integrated into a number of color vision tests, such as the well-known Ishihara plates test (Figure 148, right) (see *Common test devices and methods* section).

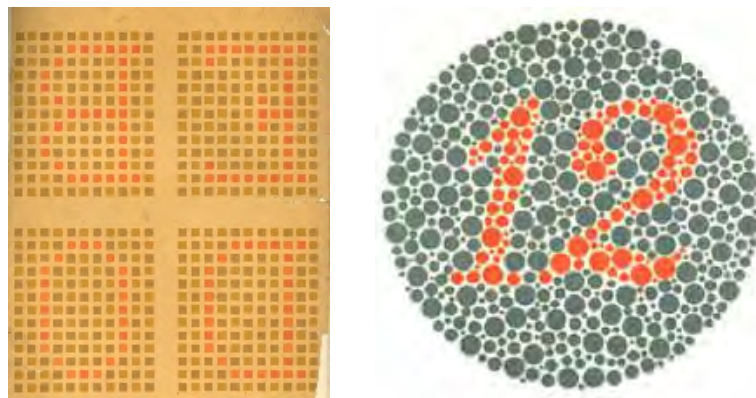


Figure 148. Examples of a Stilling pseudoisochromatic plate (left) from his 1879 publication, *Die Prüfung des Farbensinnes beim Eisenbahn und Marinepersonal* (The examination of color perception in railway and naval personnel) (left); and Ishihara plate #1 (numeral 12) (right).

In 1881, the physicist J. W. Strutt (Lord Rayleigh), working with his color mixing apparatus of narrow spectral bands of red and green used to match yellow (referred to later as a Rayleigh match), discovered a few observers made matches very different from those made by the majority of other observers. This discovery was incorporated into a color-matching device known as an anomaloscope²²³ by the German physiologist W. Nagel (1900, 1907).

In 1890s, lanterns were used by railway companies to test workers' color vision. The companies realized some of their workers could not tell the difference between certain signal lights. Lantern tests simply present colored lights (duplicating signal lights) to the observer for identification. Lantern tests are easy to administer. Their value lies in their simulation of the

²²³ The term *anomaloscope* is derived from the use of the instrument for specifying anomalous (abnormal) color vision.

working situation. Lantern tests do not explicitly screen for color defects, although it is expected observers with CVDs will not perform as well as observers with normal color vision (National Research Council, 1981).

One of the first tests of this type was the Williams Lantern Color Sense Test, developed in 1899 (Figure 149). His lantern was about twelve inches high and six inches across each face, with two discs on its front. The lower disc contained 13 colored glasses, five reds and five greens of different shades, as well as one blue, one yellow, and one colorless ground glass. The upper disc contained three shades of smoke glass and some open spaces, so by rotating these discs any of the colored glasses could be shown either alone or in combination with any of the smoke glasses to alter their intensity (Williams, 1903). The observer was required to name the presented lantern light color. A major advantage of the Williams Lantern Color Sense Test was its ability to simulate a real-life occupational situation (National Research Council, 1981). Several different models of lanterns were developed later: Giles-Archer, Edridge-Green, Martins, Sloan (Color Threshold Tester), as well as Farnsworth lanterns. The Farnsworth Lantern test, also known as the FALANT (originally FaLant), became very common for both civilian and military applications (see *Common test devices and methods* section). The FALANT was developed by Dr. Dean Farnsworth, a USN Commander who was stationed at the Naval Submarine Research Laboratory in New London, Connecticut, during and after WWII. He is well known for his development of many of the color vision tests discussed in this section.²²⁴



Figure 149. The Williams Lantern Color Sense Test.

The next significant advancement in color testing was arrangement tests (also referred to as hue discrimination tests), where the observer is required to arrange color samples by similarity in a sequential color series. Usually the colors are mounted in caps, which are numbered on the back and can (except usually for one fixed reference cap) be moved about freely during testing. The first of this type was developed by W. Pierce (1934). Similar work on arrangement tests was performed by E. Murray (1930, 1943), D. Farnsworth (1943, 1957), and Lanthony (1975). The more commonly encountered arrangement tests involving hue discrimination include those developed by D. Farnsworth (i.e., Farnsworth-Munsell 100-Hue and Farnsworth Panel D-15 [Linksz, 1966]) and P. Lanthony (1974, 1975) (i.e., Lanthony Desaturated Panel D-15 and the Lanthony New Color Test).

²²⁴ The FALANT also was known as the New London Navy Lantern (Farnsworth & Foreman, 1946).

With the rapid growth of computer technology, particularly in graphics display cards and high resolution color monitors, computerization of color vision testing has been seen as a way to overcome some of the difficulties of color vision tests, especially by making the tests more repeatable and robust (French, Rose, Thompson, & Cornell, 2008). In recent years, versions of many of the common tests, as well as new tests, have been developed for computer-based testing (Goulart et al., 2008; Rabin, Gooch, & Ivan, 2011; Ng, Self, Vanston, Nguyen, & Crognale, 2015).

Computer-based testing may offer a number of advantages (e.g., the ability to display colors impossible to print, convenient randomization of stimuli, and automatic scoring) (Ng, Self, Vanston, Nguyen, & Crognale, 2015). However, producing an accurate digital color vision test for commercial/public use is challenging because the product must be able to reproduce specific chromaticities across different computer and display hardware. The more common computer-based color vision tests include the Rabin Cone Contrast Test (CCT) (Rabin, 1997; Rabin, Gooch, & Ivan, 2011), the Cambridge Colour Test (CCT) (Mollon & Reffin, 1989), Colour Assessment & Diagnosis (CAD) Test (Barbur, Rodriguez-Carmona, Evans, & Milburn, 2009), and the Waggoner Computerized Color Vision Test (WCCVT) (Rabin, Gooch, & Ivan, 2011; Ng, Self, Vanston, Nguyen, & Crognale, 2015). In addition to these well-developed computer tests, a number of internet websites offer quick and easy color vision “tests.” However, because exact color representation on the computer display is essential for the accuracy of any color vision test, results from such online color vision tests should not be taken as conclusive and a medical professional should be consulted.

Common test devices and methods.

French, Rose, Thompson, & Cornell (2008) state “Despite the great advances in the development of colour vision tests since they were first created...there is no single colour vision test that can rapidly and accurately screen, diagnose, and classify any colour vision defect.” As a consequence, there is a great uniformity in the selection of color vision tests (and standards), and this is especially true in the aviation community (Werfelman, 2008; Watson, 2014). A literature search today will identify over 70 color vision tests and variants. This large number of tests exists because color vision can be measured in several ways, depending on the nature of the question (Elliot, Fairchild, & Franklin, 2015). Some tests can be used to separate individuals with a CVD from those with normal color vision. Other tests can measure the type or severity of a particular CVD. Some tests can perform multiple functions. The large number of available color vision tests also is supported by the fact vision specialists maintain no single color test is “all-fulfilling” (Dain, 2004). Tables 14 and 15 provide a representative list of some of the better-known tests, both past and present.

Historically, most color vision tests are categorized into four types: pseudoisochromatic plate (PIP), matching, naming, and arrangement tests (Yates & Heikens, 2001; Dain, 2004), which correlates well with the evolution of color vision tests. A fifth type category can be argued for other specialized tests such as multifunction devices and for the growing number of computer-based tests, even though many of the latter are based on the original four types. (See Tables 14 and 15). More exhaustive lists and descriptions can be found in Pokorny, Smith, Verriest, & Pinckers (1981), Birch (2001), Dain (2004), and Elliot, Fairchild, & Franklin (2015),

and well as at many professional, academic, and government websites (e.g., Aircraft Owners and Pilots Association [www.aopa.org], American Optometric Association [www.aoa.org], University of Houston College of Optometry [www.opt.uh.edu], and the FAA [www.faa.gov]).

Table 14. Selected PIP color vision tests (adapted from French, Rose, Thompson, & Cornell, 2008).

Test	Development year	Note(s)
Pseudoisochromatic plate (PIP)		
Stilling	1876	Required the identification/non-identification of numbers or shapes against a potentially confusing colored background
Ishihara	1917, 1951	Consists of 38 plates presenting a single- or two-digit number within an array of colored dots; abbreviated versions of 10, 14 or 24 plates available (Ishihara, 1951)
Dvorine	1944, 1953	One demonstration and 14 test plates (also 23-plate version); Requires the Macbeth Easel Lamp, ²²⁵ Daylight Fluorescent Tube, ²²⁶ or a 100-watt Blue-Daylight Lamp (Dvorine, 1944, 1953); more recently, the True Daylight Illuminator ²²⁷ light at 6280 °K
Hardy Rand Rittler (HRR)	1954	Twenty plates (6 screening and 14 diagnostic plates) (Hardy, Rand, & Rittler, 1954a,b)
American Optical Color Vision Test	1965	Fifteen plates (1 demonstration and 14 test); a rapid-screening test for red-green defects
Farnsworth F2, Tritan Plate	Prior to 1967	A single vanishing plate test developed by the USN to screen primarily for tritan defects (Pinckers, 1972)
Standard PIP 2 (SPP2)	1982	Used to screen for both congenital and acquired color vision defects (Hovis, Cawker, & Cranton, 1996; Ichikawa, Hukami, & Tanabe, 1983; Pinckers, Nabbe, & Vossen, 1985)
Richmond HRR	1991, 2002	Mimics original HRR but has some desaturation; performs better in differentiating protans and deutans and in grading severity (Cole, Lian, & Lakkis, 2006a)
PIP Ishihara Compatible (PIPIC)	2004	Twenty-four plates (17 adult, 7 pediatric); tests both congenital and acquired CVDs (Waggoner, 2004)

The many color vision tests also can be classified as qualitative or quantitative (Rogosic et al., 2012). Examples of qualitative tests include the PIP type tests, e.g., Ishihara PIP. Quantitative tests would include the matching (e.g., anomaloscopes) and arrangement tests (e.g., FM-100 and D-15).

²²⁵ The MacBeth Easel Lamp was designed to provide proper illumination for performing color vision screening with a variety of PIP tests. This illuminant is no longer available.

²²⁶ Daylight fluorescent tubes providing 6280 °K illumination are acceptable as MacBeth lamp replacements for PIP color tests (Dain, 1998; Dain & Honson, 1993).

²²⁷ The True Daylight Illuminator has a CRI value of 94 and is a recommended replacement for the MacBeth lamp for use with Farnsworth D15, 100 Hue, SPP2, HRR, and Ishihara tests (Bailey, Neitz, Tait, & Neitz, 2004; Dain, 1998)

PIP tests.

PIP tests, in which the observer is required to identify an object (e.g., a numeral, a letter, or a shape) embedded in a background and differentiated from it on the basis of color only, are the most widely used type of color vision test to screen for CVDs. The underlying principle is the color of the object embedded in a background of another color appears “falsely of the same color” to color-deficient observers. Object and background chromaticities are chosen carefully to be the ones confused by people with CVDs (Rodriguez-Carmona, 2015). PIP tests are relatively inexpensive, easy to administer, and have low cognitive demand, but do require attention and fixation skills (Duckman, 2006). Examples of plate type color vision tests are presented in Table 14 and Figure 150. These include the Ishihara, the Dvorine, the Hardy, Rand and Ritter (HRR), the Richmond HRR, and the Farnsworth F2 Tritan Plate.

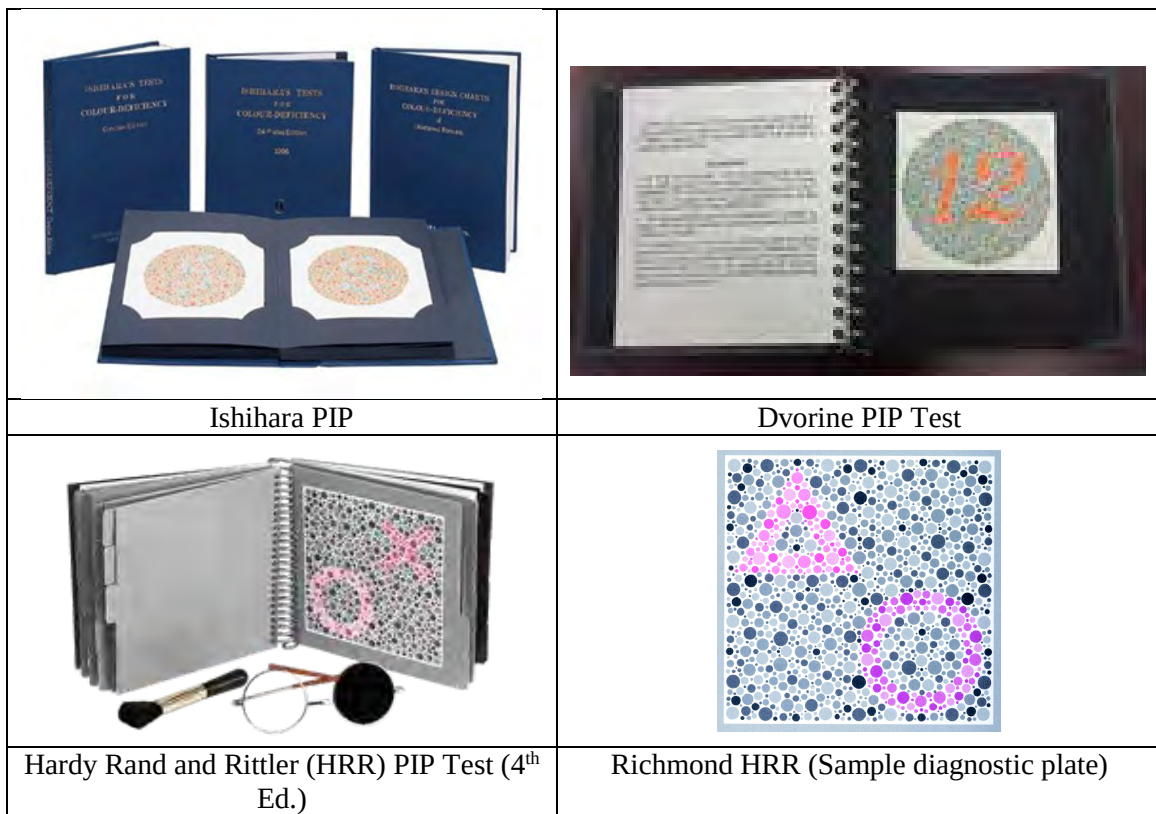


Figure 150. Examples of PIP type color vision tests.

The term “pseudoisochromatic plate” originates from the dots making up the plate design are different in color, but equal in saturation. As a result, an observer with a CVD perceives the different colors as the same color (pseudoisochromia), i.e., cannot distinguish a number, letter or figure present from the background (Wright, 1946; Sloan and Habel, 1955; Pickford and Lakowski, 1960).

Table 15. Selected (non-PIP) color vision tests (adapted from French, Rose, Thompson, & Cornell, [2008]).

Test	Development year	Note(s)
Matching		
Seebeck	1837	Consisted of a set of more than 300 colored papers
Holmgren Wool Test	1877	Consisted of 75 different colored small wool strands to be matched to three larger standard skeins, colored red, green, and purple; variants with up to 125 strands exist
Nagel anomaloscope	1907	Used to classify and grade red-green defects; based on the Rayleigh match (Nagel, 1907; Williams, 1915)
Pickford-Nicolson anomaloscope	1957	Simpler optical (no lenses) and mechanical design; in theory all color defects can be tested (Lakowski, 1969a)
City University Colour Vision Test (CUCVT)	1972 (2 nd ed.)	Eleven desaturated plates consisting of a central colored dot and four surrounding colored dots; designed for children (Fletcher, 1980)
Lovibond Color Vision Analyzer	1974	Presents 27 colors in a circular display with a central neutral gray (Dain, 1974)
Neitz anomaloscope	1980	Uses narrow band interference filters
Heidelberg (Oculus) anomaloscope	1988	Uses light emitting diodes coupled with interference filters; uses the Rayleigh equation for red-green color deficiencies (Gehring, 1988)
Naming		
Edridge-Green Lantern	1891	Seven colored glass filters and seven modifying glass filters
Giles-Archer Colour Unit	1935	A black metal cylinder with attached revolving lens disc featuring five colored lenses and one aperture (The College of Optometrists, 2017)
Martin Lantern	1939, 1943	The Martin lantern is similar to the Color Threshold Tester (CTT) except it has only four colored signals—red, green, orange, and white (Martin, 1939); has been adapted into a computerized version (Kapoor, Vats, & Parihar, 2013)
Royal Canadian Navy Colour Test Lantern	1943	Presented two horizontally lights at a time in nine color combinations; used by Royal Canadian Navy (Solant & Best, 1943)
Sloan Color Threshold Tester	1944	A lantern consisting of a black wooden box with hinged doors at each end providing access to two rotating discs of 8 filters and two control knobs; there was an internal 60-watt lamp. (Sloan, 1944; The College of Optometrists, 2017)
SAM-MacBeth Color Threshold Tester (SAM-CTT)	1943	A lantern device with eight lights (2 reds, 2 greens, 1 orange, 1 yellow, 1 blue, and 1 white); used by USAF and NASA
Farnsworth Lantern (FALANT)	1946	Red, green, and white lights presented in pairs (Farnsworth & Foreman, 1946a)
Holmes-Wright Lantern	1974, 1982	Types A and B; Type A was designed for aviation; presents two different green, two red, or a white light in pairs (Holmes & Wright, 1982; Vingrys & Cole, 1983);

OPTEC® 900 Color Vision Screener	2006	FALANT equivalent; used by USN and U.S. Army (Cole, Lian, & Lakkis, 2006b)

Table 15 (continued). Selected (non-PIP) color vision tests (adapted from French, Rose, Thompson, & Cornell, [2008]).

Test	Development year	Note(s)
Arrangement (Hue discrimination)		
Farnsworth-Munsell 100-Hue (FM-100)	1943	Four distinct rows of similar color hues, each row originally containing 25 distinct variations of each hue; later reduced to 85 hues
Farnsworth Panel (Dichotomous) D-15	1947	A shortened version of the FM-100 with one reference cap and 15 numbered moveable caps; designed for vocational use in the electronics industry
Roth 28 Hue	1966	Uses every third color cap from the FM-100 (85-color-cap) test (Amos & Piantanida, 1977; Roth, 1966)
Lanthony Desaturated D15	1978	Has desaturated colors; similar in design to the Farnsworth Panel D-15
Adams Desaturated D15	1982	Has desaturated color caps similar to Lanthony test; however cap value (lightness) matches those of the Farnsworth test
Multifunction		
OPTEC® 5000 Vision Screener	2011	Test slides made from photographic film placed between glass plates; has series of color perception and recognition slides, e.g., Ishihara PIP and tumbling “E” (Milburn & Roberts, 2013)
Computer-based		
Cambridge Colour Test (CCT)	1989	The stimulus arrays resemble the plates of a traditional PIP test, e.g., Chibert and Stilling (Mollon & Reffin, 1989)
Cone Contrast Test (CCT)	1997, 2011	A computer-based, high-resolution video controlled color vision test designed to assess individually the long (L, red), middle (M, green), and short (S, blue) wavelength photoreceptors (cones) (Rabin, 1997; Rabin, Gooch, & Ivan, 2011); currently used by USAF and U.S. Army
Colour Assessment & Diagnosis (CAD) Test	2005	Based on principle of spatiotemporal luminance masking; authorized by the United Kingdom’s Civil Aviation Authority as a color vision screening device for civilian pilots (Barbur, Rodriguez-Carmona, Evans, & Milburn, 2009)
Seohan 85 Hue Test	2007	Based largely on the FM-100 test, having 4 separate components and a total of 85 hues covering the red, green, yellow and blue spectra (Shin, Park, Hwang, Wee, & Lee, 2007)
Waggoner Computerized Color Vision Test (WCCVT)	2011	A PIP-based test with a screening section designed to detect protan, deutan, and tritan CVDs; has diagnostic sections for determination of type and severity of the CVD (Picken, Mann, & Rings, 2013)

PIP tests can include several different types of plate designs (Dain, 2004; National Research Council, 1981):

- Demonstration or malingering design: In this design, the object is defined by a substantial luminous contrast with the background, not a color contrast; and, therefore, does not require good color vision for a correct response. This plate design permits demonstration of the test procedure to both color normal observers and observers with CVDs. In addition, malingerers can be identified, since the object will be visible to all observers.
- Disappearing or vanishing design: In these plates, the object is defined by a color difference with the background; and, if the color differences are aligned on or close to the dichromatic confusion lines, the object will not be visible to protans and deuterans. Observers with good red-green color vision can see the embedded object. A shortcoming of this plate design is observers with a CVD will repeatedly not see an object and could become anxious. This design also may be slower to administer because the CVD observer may spend time striving to see an object.
- Transformation, ambiguous, or alteration design: This design elicits an alternate response from observers with a CVD, i.e., color normal observers will see one object; observers with a CVD will see a different object.
- Hidden object design: Plates of this design contain objects visible only to CVD observers; observers with normal color vision do not see an object. The object and background are constructed from a variety of colors (as observed by color normals). All the object colors lie around one confusion line, and all the background colors lie on a different confusion line. This plate design is not considered to provide very useful results.
- Classification or diagnostic design: These plates are essentially disappearing plates but with two side-by-side figures, one designed to be confused by protans (red deficient) and one by deuterans (green deficient) rather than designed to be failed by both.
- Quantitative plate design: An enhanced diagnostic design forming a series of plates with increasing color differences.
- Combination design: This design incorporates both a disappearing figure and a demonstration figure within the same plate. Accordingly, the color normal will report two objects while the CVD observer will report just one. These plates are useful because there is always something to which the CVD observer can respond.

The most widely used PIP test is the Ishihara Color Vision Test (Birch, 1997). The Ishihara test has proved to have the best sensitivity and specificity of all the pseudoisochromatic tests (Cole, 2007). The test is named after Japanese ophthalmologist S. Ishihara, who devised the procedure 1917. His plates are based on those of Stilling (Bimler, Kirkland, & Jacobs, 2000). The test exists in a standard version of 38 plates, a shorter version of 24 plates and a concise test containing 14 plates. The plates are divided between transformation, vanishing, hidden and classification plate designs, each with their own technique to enable the identification of a specific CVD. Ishihara plates can only be used to classify red-green color CVDs. Tritan defects cannot be evaluated by these tests. The object and background consist of discrete discs varying in size and luminance to ensure the object can be identified only by its chromatic difference from the background and not from a difference in the perceived luminance (Dain, 2004). The test is carried out at a viewing distance of 26 inches (66 centimeters), and the observer is allowed four seconds to identify the object (Formankiewicz, 2009). Proper testing technique also forbids any coaching, touching, or tracing of the numbers.

Ishihara plate #1, shown in Figure 151 (left), below, (and in Figure C148, right), is a demonstration plate (typically the numeral "12") designed to be visible by all persons, whether having normal color vision or a CVD. In plate #7 (a diagnostic plate) shown in Figure 151 (right), the numeral "74" should be visible to observers with normal color vision; observers with a red-green deficiency (dichromats) may see the numeral as "21."

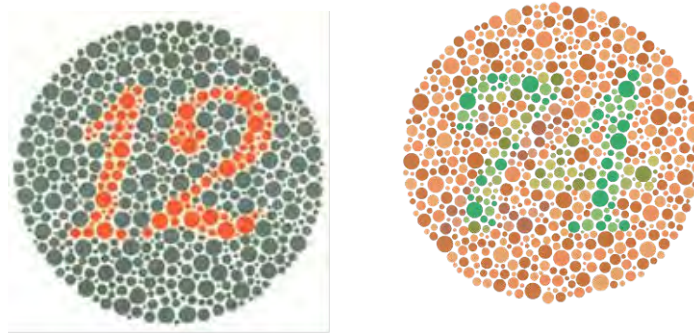


Figure 151. Ishihara plate #1 (demonstration numeral 12) (left); and plate #7 diagnostic plate), seen as "74" by color normals or as "21" by observers with a red-green deficiency.

Of the PIP tests, one of special interest to the military community is the no longer available Farnsworth F2 plate, also known as the Farnsworth Tritan plate, as the test had a single goal, screening for tritan deficiency (although it can detect some red-green deficiencies (Figure 152) (National Research Council, 1981).

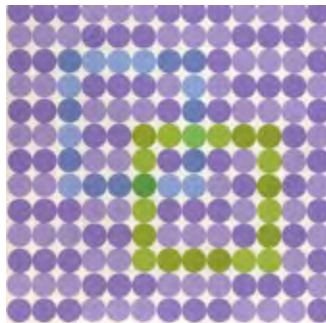


Figure 152. The Farnsworth F2 Tritan plate.

While using the F2 Tritan plate, an observer sees as many as two blue or green squares on a purple background (of dots). If the observer sees only the blue square or if the blue square is clearer than the green square, there is evidence of a tritan (blue-yellow) color defect.²²⁸ If the observer only sees the green square, a red-green deficit is present and should have been detected by other tests devised for red-green deficiencies (Pinckers, 1972; Yates & Heikens, 2001). The Farnsworth F2 plate was accepted at the time for being very effective in identifying tritan defects (Birch, 1997; Wright, 1952).

²²⁸ While frequently used, the designation of a blue-yellow defect is misleading. Individuals having the tritan color defect confuse blue with green and yellow with violet. So the term blue-green color deficiency would be more accurate because the colors blue and yellow are usually not mixed up by tritanopes.

Matching tests.

In matching tests, the observer is required to adjust two colors until they match, to report on a pair of colors as matching or not matching, or to select the best match from a number of options. Examples of matching type color vision tests are presented in Table 15 and Figure 153. The most common of these tests are devices known as anomaloscopes. Historically, these devices have used three distinct matches (or equations) used to test CVDs: the Rayleigh, the Pickford-Lakowski, and the Engelking-Trendelenburg (National Research Council, 1981).²²⁹ Of these matches, the Rayleigh match and Pickford-Lakowski match are the most frequently used today. The Rayleigh equation involves matching a spectral source near 589 nm to a mixture of spectral sources near 670 nm and 545 nm.²³⁰ With the Pickford-Lakowski equation, the match is of a white light (from a tungsten source) to a mixture of 470 nm and 585 nm sources. This match equation was designed to evaluate the effect of aging (Pickford, 1968; Lakowski, 1974) and has also proved important in evaluating color defects acquired in eye diseases (Lakowski, 1972).

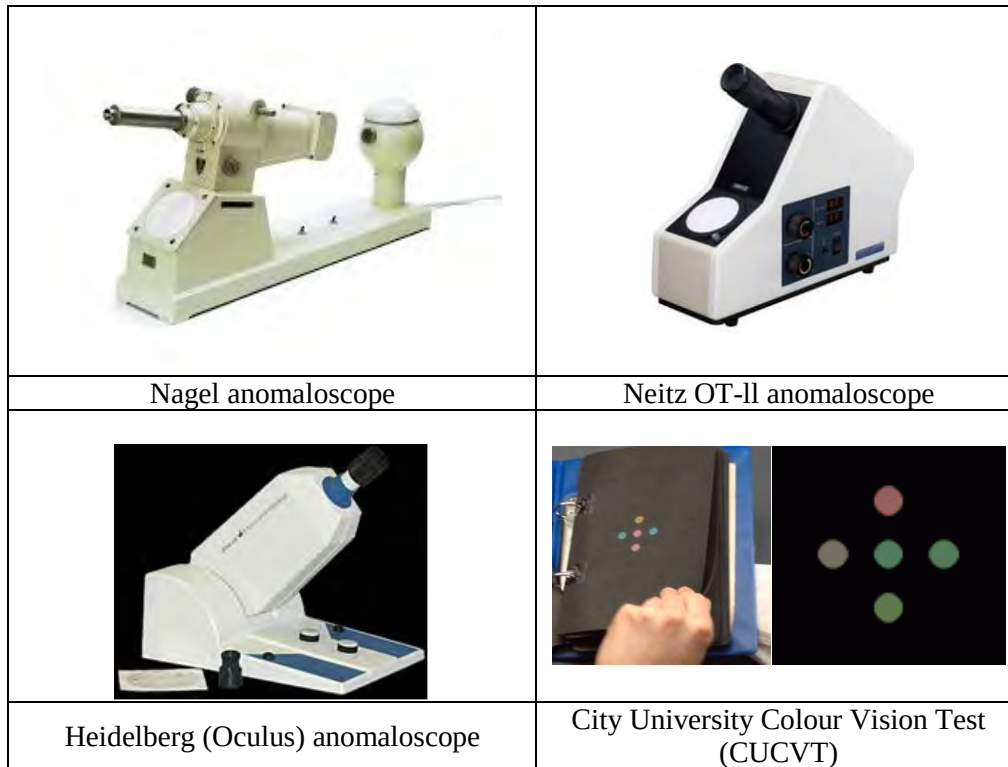


Figure 153. Examples of matching type color vision tests.

Generally considered to be the “gold-standard” in the diagnosis of CVDs, the anomaloscope is frequently used for comparison with new color vision testing devices and methods (Moreland, 1984; Ivan, Yates, Tredici, & Gooch, 1994; Dain, 2004). The anomaloscope provides the most accurate possibility to test the severity of color blindness and distinguish between dichromats and anomalous trichromats. However, anomaloscopes are expensive

²²⁹ Additionally, there is a fourth equation, the Moreland blue-green, that matches indigo (436 nm) and green (490 nm) to cyan standard (480 nm plus 580 nm mixed in a fixed ratio (Sharpe, Stockman, Jagle, & Nathans, 1999).

²³⁰ The wavelengths cited here are for the Nagel Model 1 anomaloscope in current production. Wavelengths have differed in various instruments.

devices; examination using these devices is time-consuming; and trained operators are required (Rogosic et al., 2012).

The procedure for using the anomaloscope is for the observer to view a circular color pattern via an eyepiece (Wright et al., 2016). The viewing field is composed of two adjacent semicircles (Figure 154). The upper semicircle is filled with a mixture of spectral green (545 nm) and spectral red (670 nm). The lower semicircle is filled with spectral yellow (589 nm) of variable luminance. Two control knobs are provided: one allows for adjustment of the red (R) and green (G) mixture; the other knob controls the yellow luminance. The yellow luminance control is used to adjust for a perfect match, referred to as the “matching midpoint.”



Figure 154. View through the eyepiece of an anomaloscope.

Anomaloscopes encountered in the literature include the Heidelberg (Oculus) (which uses LED light sources), Kaplan, Nagel, Neitz, Pickford-Nicolson, and Schmidt-Haensch, with the Nagel being the best known.

Another matching test is the City University Colour Vision Test (CUCVT) (Figure 153, bottom, right), although not strictly a matching test but it is a forced choice test of which color is the closest match. It was designed to detect color confusions (i.e., colors that appear quite different to the normal observer but appear similar to the defective observer). It is derived from the colors of the Panel D-15 test. Five colors are presented on each page, and the observer has to indicate which of the four surrounding colors are closest in color to the fifth, centrally placed color. One of the choices is the adjacent D-15 hue (the correct choice with normal color vision), and each of the surrounding choices lies on one of the protan, deutan and tritan confusion loci. This test is similar in difficulty to the D-15 but has the useful advantage of the observer not handling and soiling the color areas (Dain, 2004). Initially, the test was comprised of 10 plates, but other versions with less plates exist. Although classification of congenital protan and deutan deficiency is inexact, the CUCVT is useful for acquired defects (Heron, Erskine, Farquharson, Moore, & White, 1994).

Naming tests.

Naming (sometimes referred to as occupational) tests are color vision tests where the observer must name a color correctly and/or respond with an appropriate action arising from correct identification of the color (e.g., stop, start) without necessarily naming the color. Color naming tests historically have been useful in occupational situations (e.g., railways, maritime and driving) but are considered to be unreliable in detecting congenital CVDs, as observers develop strategies to defeat them (Dain, 2004). Examples of naming type color vision tests are presented in Table 15 and Figure 155.

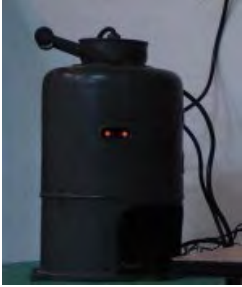
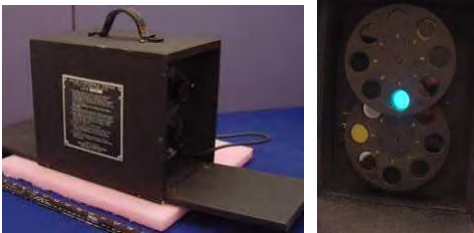
	
Edridge-Green Lantern	Farnsworth Lantern (FALANT)
	
Martin Lantern	Giles-Archer Colour Unit
	
SAM-MacBeth Color Threshold Tester	Sloan Color Threshold Tester

Figure 155. Examples of naming type color vision tests.

Lantern tests are the most common naming tests. They almost universally consist of a series of small colored lights (sometimes point sources), or combinations of pairs of colored lights, being shown to the observer, who sits at a set distance from the lamp. The observer has to name the color of each light. Incorrect naming of some colors indicates a CVD. The lights are

designed to simulate signal lights used in various occupations and their colors are chosen appropriately (Squire, Rodriguez-Carmona, Evans, & Barbur, 2005). Several factors influence performance, including visibility as well as color identity. Response times to these tests have an important bearing on real-life situations (Fletcher, 2002). The number of variants of lanterns tests rival PIP tests. In the railroad and maritime industries, they were the most prevalent and most used occupational color vision tests.

In many settings, lanterns tests frequently serve as secondary tests, with specific types approved for use varying with the defined color-critical tasks. Lantern tests have a long history as occupational tests and are accepted by many regulatory bodies. There are eight different lantern tests currently in use: the Holmes-Wright type A (aviation) and B lanterns, the FALANT, the OPTEC® 900 Color Vision Screener,²³¹ the Aviation Lights Test (ALT) (Milburn & Mertens, 2004), the Fletcher Clinical Aviation and Maritime (FCAM) (Fletcher, 2005), the Beyne, and the Spectrolux® lanterns. All usually present pairs of lights each of which may be standard aviation colors of red, green or white, and require the observer to name the colors. They vary widely in the level of difficulty they present and many are no longer made. These lantern tests do not test for blue-yellow (tritan) defects, cannot be used to identify the type of CVD or quantify severity, and there is limited evidence on their diagnostic accuracy (Cole, Lian, & Lakkis, 2006b; Bailey & Carter, 2016).

Lantern tests present differing levels of difficulty (Cole and Vingrys, 1982), and the various administering authorities may adopt different test procedures for a particular lantern, as well as different criteria for failing (Forsey & Lane, 1956). For example, the Royal Navy and Royal Air Force (RAF) both have used the Holmes-Wright Type A lantern (Cole & Vingrys, 1983). A lantern test is usually more difficult in a bright room. Observing in complete darkness may give the best chance of success. However, there is evidence subjects with CVDs may have reduced recognition of colors in a dark environment (Fletcher, 2002; Holmes & Wright, 1982; Kapoor, Vals, & Parihar, 2013).

While many lantern tests are no longer in production, newer variants are still used in the transport, maritime, aviation and naval industries.

Arrangement tests.

In arrangement tests, the observer is required to arrange a set of colors into an ordered sequence based (usually) on hue or to group colors by some attribute (most often colors separated from grays) (Dain, 2004). These tests are usually along a specific test strategy: hue discrimination, color confusion, or evaluation of neutral zones (colors seen as gray) (Yates & Heikens, 2001). Examples of arrangement tests include the FM-100 Hue (hue-discrimination), Farnsworth Dichotomous D-15 (color confusion), Lanthony Desaturated D15 (color confusion and neutral zones), and the Roth 28 Hue (hue discrimination). See Table 15 and Figure 156.

²³¹ The OPTEC® 900 and the Aviation Lights Test are newer version of the original FALANT.

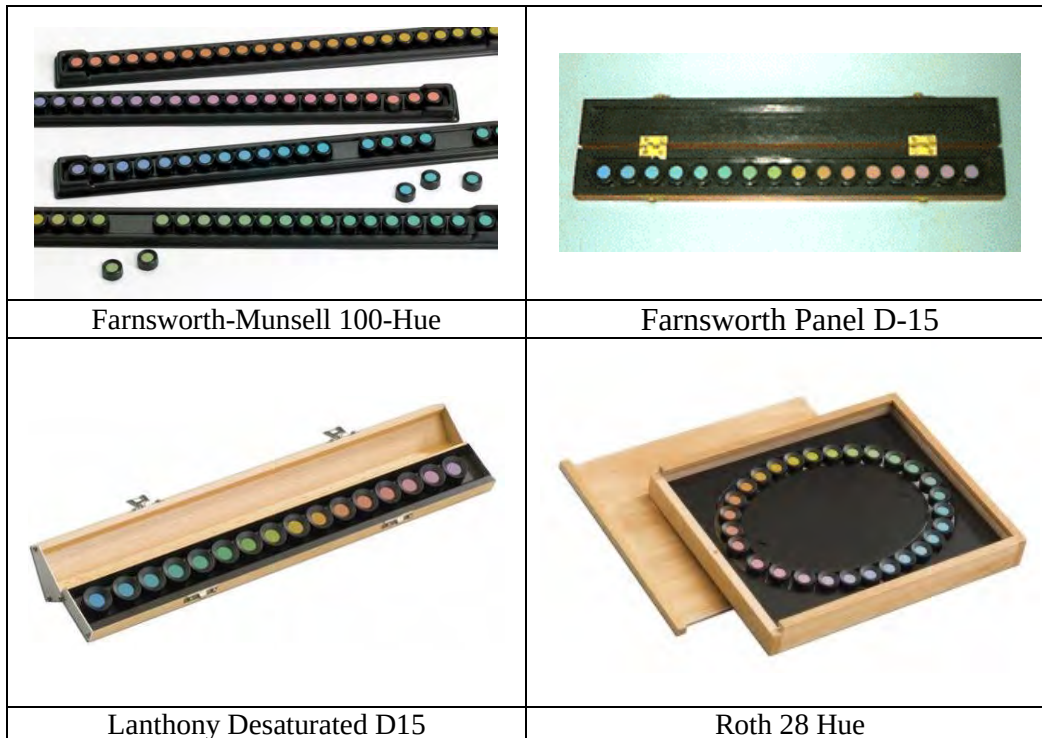


Figure 156. Examples of arrangement type color vision tests.

Arrangement tests have the advantage of being easy to administer to naive observers. Disadvantages include possible damage to hue pigments during handling and the requirement of special sources of illumination.

The FM-100 Hue test remains the most comprehensive color vision test available and the best known. It is based on hue discrimination and is a quantitative test. It has an established history of use in detecting both hereditary and acquired CVDs. It was developed by D. Farnsworth in 1943. It is an example of a color order system based on equal perceptual steps (Dain, 2004). Using the Munsell color notation, the five basic hues (i.e., red-R, yellow-Y, green-G, blue-B, and purple-P), these are partitioned by five more hues, RY, YG, GB, PB and RP. Each of the 10 hues is subdivided into 10 levels. Therefore, there are a total of 100 hues. Farnsworth found the difficulty of distinguishing between adjacent hues was not equal around the hue circle. Therefore, he removed 15 hues in an attempt to make the color spacing more uniform. The chromaticities of these hues are plotted on the 1976 CIE u', v' chromaticity diagram in Figure 157. The chromaticities of the fixed hues are indicated by solid dots.

Farnsworth divided the 85 colors into four boxes (i.e., hues 85 to 21, 22 to 42, 43 to 63, and 64 to 84). Each box has a fixed hue at each end, one removed from the first and last moveable hues in the respective box (Figure 156, top, left). The task of an observer is to arrange the moveable hues to provide a gradual, ordered progression between the two fixed hues.

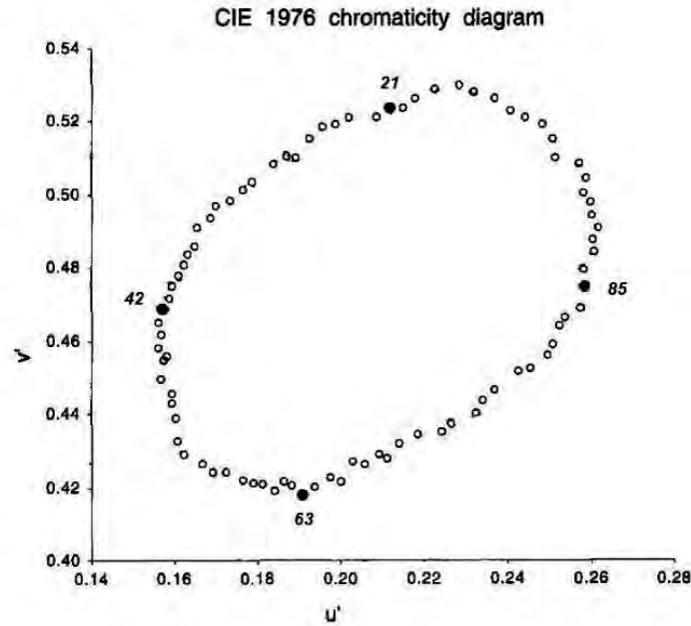


Figure 157. The FM-100 Hue test chromaticities plotted on the 1976 CIE u', v' diagram.

The FM-100 is a very sensitive color vision test; it is also very tedious and time-consuming. To address these issues, Farnsworth explored tests using fewer Munsell hues. One of these was the Farnsworth Dichotomous Panel D-15 Test, developed in 1947, and consisted of 16 hues: one fixed hue and 15 moveable hues (Figure 156, top, right). An observer was directed to order the hues starting with the fixed hue. Farnsworth's D-15 test is called dichotomous because it was designed to separate persons tested into one of two groups: 1) strongly color deficient or 2) mildly color deficient and/or color normal. The test can indicate red-green discrimination loss, as well as blue-yellow discrimination loss and monochromacy (Bassi, Galanis, & Hoffman, 1993; Oliphant & Hovis, 1998). The observer is allowed as long as is necessary to complete the task but is almost always completed in much shorter times than with the FM-100 Hue Test. However, sensitivity is reduced. There are several versions of this test in circulation and a "desaturated" version, using the same hues but with lower saturation, is often used.

As a compromise between the tediousness, high time demand, but high sensitivity, of the FM-100 and the speed but reduced sensitivity of the Panel D-15 Test, Roth (1966) modified the FM-100 Hue Test to create a sub-set known as the Roth 28-Hue Test (Figure 156, bottom, right). This test uses every third disc of the FM-100 and gets his name from the resulting 28 colored discs. The administration procedure for this test is similar to most all arrangement tests and can serve as an example of their ease of use:

The Roth's 28 colored discs are numbered on the bottom. The test is intended to be administered on a black background to prevent surroundings from affecting the color perception by the observer. As with many color tests, it is very important to administer this test under consistent conditions in order to provide validity to subsequent retesting over time. Test illumination should provide approximately 6700 °K at 25 fc or greater (Illuminant C) or daylight. Both the examiner and the observer should wear some type of finger covering (e.g., gloves) to prevent direct handling of the color discs. The test

procedure begins with the examiner removing the reference cap (#1) from the box, tipping one end of the box so as to place the remaining color discs onto a black surface, color side up. The #1 cap then is replaced into the box. The examiner then mixes up the remaining discs before beginning the test. The observer is instructed to select the color disc from those remaining which most closely matches the reference cap and place it into the box next to the reference cap. The observer then continues to select the next closest color disc and places each in sequence into the box. The observer is allowed a reasonable time to arrange the discs and is permitted to alter the sequence prior to completion. Completion time should be approximately two minutes and should not be unlimited. Scoring for each case is accomplished by reading the color disc numbers as arranged by the observer and recording them on the score sheet. When not in use, the test discs should be stored in a cool dry place, protected from sunlight.

In general, arrangement tests use a variety of Munsell hues of the same saturation and luminance. The hues are chosen to be distributed around a complete circle surrounding the equal energy white point in the CIE diagram. Arrangement tests are particularly useful for evaluating patients with eye disease because their demands on acuity are low, and no specific color confusions are predicted (Foster, Krastel, & Moreland, 1991; Pacheco-Cutillas, Edgar, & Sahraie, 1999).

Multifunction and computer-based tests.

Multifunction and computer-based testing make up an additional type of color tests (Table 15). An example of a multifunction color testing device is the OPTEC® 5000 Vision Screener (Figure 158, bottom, left). This device is related to the OPTEC® 2300 Armed Forces Vision Tester, the only vision screener exclusively manufactured for the U.S. military. The 5000 model supports an additional series of color perception and recognition slides, e. g., Ishihara PIP and tumbling “E” (Stereo Optical Company, 2009). The 5000 model has replaced the four 7-watt incandescent bulbs used in earlier models with four LEDs as the method of illumination of the test slides. It has been reported the difference in color rendering (e.g., CRI) between the source types has adversely affected the color appearance of the pseudoisochromatic plates used for color vision screening, reducing the test’s specificity (Milburn & Roberts, 2013). The characterization of CRI for LED technologies is still a challenge, and addressing this issue may very likely solve the color rendering problem.

After almost a century of color vision testing with essentially the same battery of tests (or variants thereof), a host of computer-based color vision tests have been devised. While offering a number of advantages, they have yet to be fully accepted by the testing community (Ng, Self, Vanston, Nguyen, & Crognale, 2015). Computer-based tests are appealing for a number of reasons (e.g., the ability to display colors impossible to print, convenient randomization of stimuli, and automatic scoring). However, producing an accurate digital color vision test for clinical and research use is challenging because the test must be able to reproduce specific chromaticities while using many different computer and display hardware (Hasrod & Rubin, 2015).

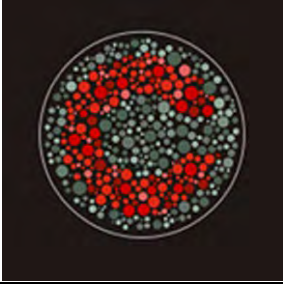
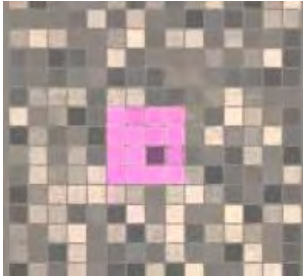
	
Cambridge Colour Test (CCT) Landolt C Target	Cone Contrast Test (CCT)
	
OPTEC® 5000 Vision Screener ²³²	Colour Assessment & Diagnosis (CAD) Test target

Figure 158. Examples of multifunction and computer-based color vision tests.

There have been a number of attempts to develop inexpensive, non-commercialized methods of color testing using personal computer (PC) hardware and software (Kapoor, Vats, & Parihar, 2013). A. Toufeeq in 2004 has described a PC based system for the detection of color defects. Miyahara, Pokorny, & Smith (2004) developed a computerized, automated system to diagnose red green color defects using a CRT screen. Many of these efforts have involved direct emulations of existing tests, e.g., CUCVT, Ishihara plates, and HRR plates. Most of these being produced on 24-bit color displays calibrated to a standard display white (D65), with test plate images produced with a color scanners (Ing, Parker, & Emerton, 1994). As might be predicted, results have ranged widely. Reconciling human-eye and computerized color matching is a difficult task (Yap, Sim, Loh, & Teo, 1999). The computerization lantern tests also have been attempted, e.g., a computerized color vision test as a replacement for the Martin Lantern Test, with reportedly high accuracy and consistency (Kapoor, Vats, & Parihar, 2013).

Four computer-based color vision tests have risen from the group of offerings and gathered the most attention. These are (in order of approximate year of development):

- The Cambridge color test (CCT) (1989) (Figure 158, top, left) was developed by Regan, Reffin, & Mollon (1994) at the University of Cambridge, England. The test provides 14-bit color and luminance control on a calibrated CRT display. It is based on pseudoisochromatic principles. Each plate presents a Landolt C²³³ stimulus

²³² The OPTEC® Vision Screeners are manufactured by Stereo Optical Co., Inc., 8623 W. Bryn Mawr Ave, Chicago, IL, 60631.

²³³ The Landolt C is a detection target constructed on a 5 x 5 grid with the gap the width of 1 grid unit. The observer must identify the position of the gap, which is usually one of four possible positions: right, down, left, and up.

composed of randomly generated dots (varying in luminance) against an achromatic background. The chromaticity of the Landolt C target is varied along the protan, deutan, and tritan lines of a chromaticity diagram. The observer must indicate the position of the target gap. Discrimination thresholds are measured using a psychophysical staircase procedure. French, Rose, Thompson, & Cornell (2008) report the CCT has been found to be valid in assessing all CVDs.

- The Cone Contrast Test (CCT) (1996, 2011) (Figure 158, top, right) originally was developed at USAARL by J. Rabin (1997) and recently optimized by USAF School of Aerospace Medicine (USAFSAM). The CCT is a computer software-generated clinical color vision test that indicates type (red, green, or blue) and severity (mild to severe) of CVD and quantifies normal color performance (Rabin 2004; Rabin, Gooch et al. 2010). This test presents a random sequence of colored letters visible to only one cone type at a time, to provide cone-specific numeric scores. These scores then are used to detect and monitor disease and/or potentially to help determine an observer's ability to perform certain job functions. The CCT accurately detects hereditary color vision loss and reveals loss acquired (even temporarily) from disease, trauma, certain medications, and environmental conditions such as hypoxia, atmospheric pressure, and acceleration (Luria, 1992). In 2011, the USAF transitioned to computer-based testing, with the Rabin Cone Contrast Test (RCCT)²³⁴ designated as the sole approved device for assessment of color vision for aircrew personnel and applicants to aircrew positions (U.S. Air Force, 2015). In this adopted commercial version of the test, using the staircase mode, a single letter stimulus is presented to an observer for 4 seconds against a gray background. The chromaticity of the stimulus and background is selected so only a single normal cone type (L, M, or S) is sensitive to the target. The observer identifies the stimulus by using a mouse to select the matching letter from a 10-letter answer template. If correct responses are given, the contrast of the stimulus is decreased in a staircase fashion; similarly, the contrast is sequentially increased with incorrect responses. Step-wise adjustments of contrast for each chromaticity being tested provide an estimate of the just-noticeable contrast for each cone type.²³⁵ Testing is performed at 36 inches (~91 centimeters) under monocular conditions. Testing time is given as six minutes (Rabin, Gooch, & Ivan, 2011).
- The Colour Assessment & Diagnosis (CAD) (2005) (Figure 158, bottom, right) originally was developed by Barbur, Harlow, & Plant (1994) at City University, London. The test is designed for CVD diagnosis and determination of severity, not unlike existing tests, e.g., the Farnsworth D-15 test or the Nagel Anomaloscope. The design of the test is based on studies of camouflage, which have shown individuals with CVDs to have difficulties finding objects of certain colors in everyday life when

²³⁴ To reduce confusion with the Cambridge Colour Test, also identified with the acronym CCT, the Rabin Cone Contrast Test sometimes is identified by the acronym RCCT.

²³⁵ R. Ranaudo provides a personal experience where this type of testing has practical application: "Several years ago I was safety chase aircraft for a flight test of an experimental engine mounted on the wing of a test aircraft. As the test proceeded, the aft part of the nacelle started to change from white (paint color) to a brownish hue due to an exhaust gas recirculation from of increasing airspeed. The change was very gradual, and it took several minutes before the "just noticeable" difference threshold was reached for me – and I reacted. In reality, about the time I said something to the flight crew of the test aircraft, their overheat alarm was going off. However, I do realize JNDs also are a function of rate of change before sensory discrimination becomes apparent" (personal communication, November 30, 2017).

those objects are defined by color but embedded in a multicolored background where brightness is varying randomly, e.g., fruit in trees (Barbur, Harlow, & Plant, 1994; Barbur, Rodriguez-Carmona, Evans, & Milburn, 2009). The computerized (web-based) version (2005) uses a color square moving against a flickering luminance contrast noise background. The color of the square changes along different chromaticity directions. Observers with normal color vision can easily see the moving square; observers with varying levels and forms of CVD will have difficulty distinguishing movement of the square at various times during the test sequence, not unlike legacy clinical tests (Brookes, 2015). The CAD test has been found reliable in identifying protanopia and deuteranopia (Seshadri, Christensen, Lakshminarayanan, & Basi, 2005). The test has been adopted by the United Kingdom CAA as an authorized color vision screening test for civilian pilots (Barbur, Rodriguez-Carmona, Evans, & Milburn, 2009; Wright et al., 2016).

- The Waggoner Computerized Color Vision Test (WCCVT) (2011) is a newer PIP color vision test with a screening module designed to detect protan, deutan, and tritan CVDs. Additionally, it has diagnostic modules that allow the determination of type and severity of the CVD identified by the screening section. The test presents a digitized version of PIP-based plates and uses targets and background colors that take advantage of confusion lines within the CIE color space. A hidden image (numeral) is presented for 2 seconds and then replaced by a template of eight possible answers. Subjects are given unlimited time to identify the number seen in the image (or no number). The first module consists of 25 images with an additional sample image that can be seen by both color normal and color deficient observers. Observers who do not correctly identify a minimum criteria (21 plates) are given two sets of 32 desaturated slides intended to delineate between a deutan and protan deficiency, with the diagnosis based on the lower score of the two slide sets. All observers also are given a set of 12 slides that tests for a tritan deficiency and requires nine or more correct responses to pass. Testing is performed under binocular conditions at a distance of 24-30 inches (61-76 centimeters) in a darkened room. Ng, Self, Vanston, Nguyen, & Crognale (2015) report “The (Waggoner) CCVT achieved high sensitivity and specificity not statistically significantly different compared with the Ishihara and HRR tests.” The USN has been evaluating this test for the screening of aircrew members (Picken, Mann, & Rings, 2013).

A current review of the color vision literature reveals a surge in interest in replacing the many classic but no longer commercially available color vision tests with quicker, more accurate, and much easier to operate replacements, which leverage off of today’s computing and display technologies. The decades old PIP and arrangement tests are being replicated on computer screens (Cavanagh, Maurer, Lewis, MacLeod, & Mather, 1986; Inam, Marey, Semary, & Mandou, 2015; Isik & Oz, 2016; Isik, Ozcerit, & Erdurmuş, 2016). Even the “gold standard” anomaloscope (e.g., the Pickford-Nicholson anomaloscope [Pickford & Lakowski, 1960]) has been simulated on CRT and LCD monitors (Hasrod & Rubin, 2015).

An underlying theme in this section is the existence of so many color vision tests but the failure of any single test to provide a moderately simple and rapid evaluation of total color vision

performance. Although, it should be noted one of each type of test has gained prominence: pseudoisochromatic plate (PIP) – Ichihara PIP; matching – Nagel anomaloscope; arrangement – Farnsworth-Mussel FM-100 Hue Test; and naming – Farnsworth Lantern Test. The basis of this failure lies first in the complexity of color vision, being an interaction between physics, physiology, and perception. But more importantly is there are three strategies to be considered in color vision assessment: hue discrimination, color confusion, and evaluation of neutral zones (colors seen as gray)s. Each of the conventional tests is able to adopt only 1-2 of these strategies. Computerized testing may be able to combine multiple strategies. (See Issue #4 in *New and Continuing Color Issues and Future Research* section.

These computerized and web-based color tests are still undergoing rigorous evaluations, but appear to be performing well in comparison to the historical benchmarks of the anomaloscope, FM-100, and Ishihara PIP tests (Ng, Self, Vanston, Nguyen, & Crognale, 2015; Wright et al., 2016). Such tests may be able to not only detect CVDs but to diagnose their type and severity. These tests may be essential in the development of visual testing to address today's modern battlefield where low visibility, hypoxia, directed energy weapons, night imaging systems, and the use of fatigue countermeasures (Rabin, Gooch, Ivan, Harvey, & Aaron, 2011). One computer tablet application based on the Rabin CCT already has been demonstrated for clinical application with expectations a more ruggedized, portable version may prove useful for deployments, space and aviation cockpits, as well as accident and sports medicine settings (Chacon, Rabin, Yu, Johnson, & Bradshaw, 2015).

Color Snellen charts.

Arguably, even for individuals who have never seen a vision specialist, they will instantly recognize the Snellen eye chart used to measure visual acuity (a measure of the ability to see detail, or more rigorously a measure of the spatial resolution of the visual processing system). The Snellen chart is named after the Dutch ophthalmologist H. Snellen who developed it in 1862 (Snellen, 1862).²³⁶ While hundreds of versions exist today, in its most basic form, it consists of 11 rows of standardized letters (referred to as optotypes),²³⁷ subtending smaller and smaller visual angles from top to bottom (Figure 159 (top, left)). The top row is a single letter, "E." In the U.S., the standard placement of the eye chart is on a wall 20 feet away from the observer. Normal visual acuity, expressed as 20/20 vision, means the observer can read at 20 feet a letter that most individuals should be able to read at the same distance, 20 feet.²³⁸ In contrast, a 20/40 vision, means the observer can read at 20 feet a letter that most individuals should be able to read at 40 feet. A search of eye chart products will return charts similar to the example in Figure 159 (top, left).

While extremely limited in capability, one example of an available Snellen color vision chart is shown in Figure 159 (top, right); the color vision testing component consists of only a green and red bar. In Figure 159 (middle, left), a slight more sophisticated, but still limited in its effectiveness in the diagnosis of CVDs, is shown. It is accompanied by claims it can be used to

²³⁶ Kuchler, a German ophthalmologist, designed a chart in 1836 using figures cut from calendars, books, and newspapers glued unto paper in rows of decreasing size. These figures included cannons, guns, birds, farm equipment, camels, and frogs. He continued to refine his chart, and in 1843, published a new version using 12 rows of black letters decreasing in size. His chart was not widely adopted. (Frear, 2015)

²³⁷ Optotypes are usually letters, numbers, or geometric symbols.

²³⁸ 6/6 is used in countries that use metric units (6 meters).

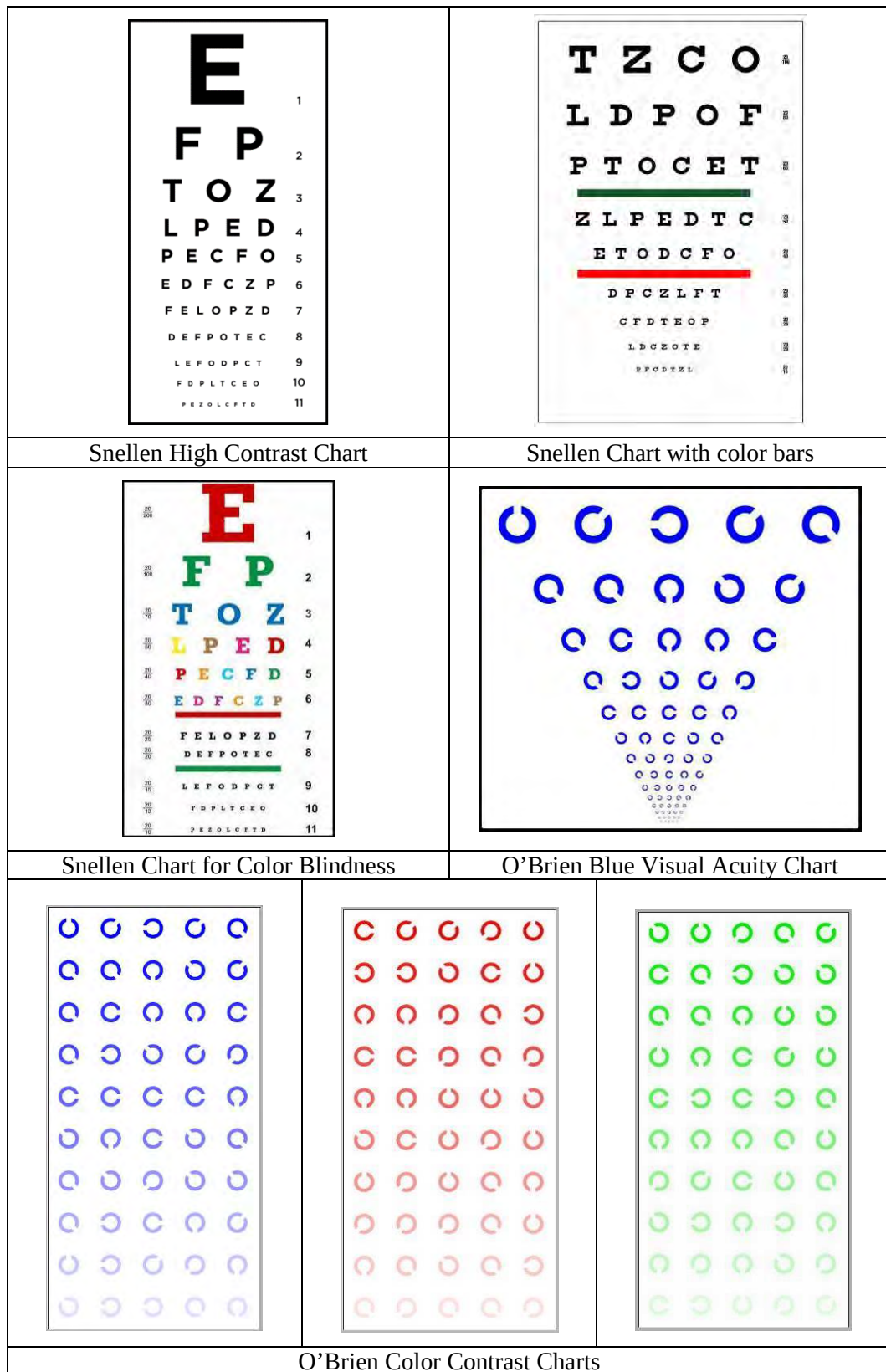


Figure 159. Color visual acuity charts.

screen for the two most common types of red-green color blindness: protanopia and deuteranopia, as well as the extremely rare total color blindness, achromatopsia.

Though any assessment method has its limitations, printed charts of optotypes have remained popular in clinical and other screening applications due to low cost, portability, and ease of use. In applications where candidates are being screened for disqualifying conditions, there is always the concern the optotype sequence will either be known in advance (such as when details of an examination are a matter of public record or can be shared between candidates) or retained between testing sessions. While many computer-based tests use randomization procedures to circumvent this issue, procedurally-generated, randomized, printed charts offer a solution in applications where digital assessment methods are unsuitable. By using vector graphics, charts can be generated quickly for a nearly infinite number of randomized optotype orders, file sizes can be kept low, but the results can be printed as charts of any needed size (within the limitations of the printer) for applications ranging from near-vision assessments to long-distance, outdoor testing (Kevin O'Brien, personal communication, October 10, 2017).

The remaining charts in Figure 159 show experimental attempts by K. O'Brien at developing computer-presented (or printed) charts for single-color visual acuity (middle, right) and color contrast sensitivity (bottom row). Both chart types have a standard LogMAR spacing²³⁹ and use an eight-alternative forced choice (8-AFC) Landolt C stimulus. For the black charts, all color channels are weighted equally in RGB space. For the colored charts, individual color channels are isolated. For the contrast chart, the first row is maximal contrast and then with each row contrast drops off by 25 units in a 0-255 scale.

Regardless of the test or tests adopted for color screening and diagnosis, such test(s) must be accessed for validity (does the test measure what is needed for the color task of issue) and reliability (whether the test measures the same property on each iteration) (National Research Council, 1981).

Military color vision testing and standards.

Color vision testing has been around since the first world war (WWI) (Harrington, Deimler, Harris, & Iavecchia, 1985). The recognition of the importance of being able to see color in the military setting is illustrated by a quote by Col. W.H. Wilmer and Maj. C. Berens in 1919 (Office of the Director of Air Service, 1920):²⁴⁰

"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."

²³⁹ When using the LogMAR chart, visual acuity is scored with reference to the Logarithm of the Minimum Angle of Resolution. LogMAR Visual Acuity = $0.1 + \text{LogMAR value of the best line read} - 0.02 \times (\text{number of letters read})$.

²⁴⁰ As documented in Ivan, Yates, Tredici, & Gooch, 1994.

Following through on this proclamation was more difficult. The more familiar tests of today were not developed until WWII, leaving only the Stilling PIP (1876), the popular Edridge-Green Lantern (1891), the very reliable but expensive and therefore not widely available Nagel anomaloscope (1907), the somewhat unreliable colored wool and bead tests and lesser known color tests. One of these tests was the Jennings Self-Recording Color Test (patented in 1914). The test was conducted by placing a perforated cardboard chart exhibiting confusion colors (basically red and green) before the candidate with one perforation corresponding with each color and shade. When presented with a color, the candidate was asked to name it by punching through a perforation. These punches were recorded on a blank sheet beneath the chart so arranged as to show whether or not they were punched correctly (Patten, 1917).

Sets of this test were bought in relatively large numbers by the U.S. Army and USN, including aviation branches, and was endorsed by the Ophthalmic Section of the American Medical Association (Association of Military Surgeons of the United States, 1917; Jennings, 1931). The test was revised in the 1920s after criticism of the color selections and was for available throughout the 1940s (Jennings, 1922). After WWI, it was recommended the Ishihara PIP test be adopted for aviation (Simpson, 1935).

U.S. Army Medical Department records of the period state: “Color vision should be normal for red and green. A Jennings test set is preferred. If not available, then 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, colored lights at 20 feet should be used as a test before rejecting” (Lynch, Weed, & McAfee, 1923). Needless to say, color testing during this period was conducted conscientiously but with questionable validity.

It would be WWII that would produce a flood of color vision tests. When the research section of the Army Air Forces School of Aviation Medicine was established in December 1941, a major goal was the selection of tests to identify red-green color vision for use in screening of aviation personnel (Sloan, 1946). At that time, four tests of color vision were authorized for use in the Army Air Forces: two basic tests and two secondary tests. The basic tests were the Ishihara test (8th Edition) and the American Optical Company Pseudo-Isochromatic Plates. However, it was uncommon to still encounter the Stilling PIP, Holmgren yarn matching, and various lantern tests (Department of the Army, 1940).

Between 1942 and 1945, numerous tests were investigated, such as the American Optical PIP, Rabin polychromatic plates, School of Aviation Medicine (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. In addition, a number of lantern tests were evaluated. The sum of these investigations was the American Optical Abridged Set of PIP was selected as the most suitable basic test (Ivan, Yates, Tredici, & Gooch, 1994).

Two years after WWII, in September 1947, the USAF was formed as a separate branch of the War Department, and aviation color vision testing began to take different paths. The following list summarizes color vision tests used by the U.S Army Air Corps and U.S Air Forces from 1918 until the formation of separate aviation branches (Tredici, Mims, & Culver, 1972):

- 1918 Jennings' Self-Recording Color Test
- 1935 Ishihara PIPs
- 1941 Ishihara or Stilling PIPs
- 1942 Ishihara - American Optical Company PIPs
- 1943 American Optical Company PIP Test (17 test plates, 2 demonstration plates);
- Mid-1940s SAM-MacBeth Color Threshold Test (CTT)²⁴¹ quantitative test (limited use)

U.S. Army.

The current U.S. Army color vision test methods and standards are given in Army Regulation 40-501, Medical Services Standards of Medical Fitness (last updated 14 June 2017). For enlistment, vision requirements for color vision are (Chapter 2, Section 2-13[f]):

Color vision. Failure to pass a color vision test is not an automatic disqualification. Although there is no standard, color vision will be tested because adequate color vision is a prerequisite for entry into many military specialties. However, for entrance into the U.S. Military Academy (USMA) or Army Reserve Officers' Training Corps (ROTC) or Officer Candidate School (OCS) programs, the inability to distinguish and identify without confusion the color of an object, substance, material, or light that is uniformly colored a vivid red or vivid green does not meet the standard.

For aviation, Chapter 4 of AR 40-501,²⁴² Medical Fitness Standards for Flying Duty, lists medical conditions and physical defects that are causes for rejection in selection, training, and retention of aircrew, where the term “aircrew” applies to rated and non-rated personnel in aviation service, unmanned aerial systems (UAS), and ATC. Section 4-12(5), states:

Color vision. (See also Army Aeromedical Technical Bulletin [ATB] – Color Vision Testing and Aeromedical Policy Letter (APL) – Color Vision Abnormalities²⁴³ (U.S. Army Aeromedical Activity, 2015).

- (a) Five or more errors in reading the 14 test plates of the Pseudoisochromatic Plate (PIP) Set; or
- (b) Any error in reading the nine test light pairs of the Farnsworth Lantern (FALANT) or the OPTEC 900 Color Vision Tester.

The PIP is the Army’s primary color vision test for the flying duty medical exam (FDME). The plates should be viewed at a distance of 20-30 inches under proper illumination (MacBeth easel lamp, indirect sunlight, or fluorescent light). Incandescent lighting should not be used as this may allow mild deuteranomalous (green weak) individuals to pass. Each eye should be tested separately. Greater than 2 errors out of the 14 plate set or greater constitutes a failure of

²⁴¹ This lantern test was developed for the USAF to determine quantitatively whether applicants with CVDs were able to meet the color perception requirements of a particular job. The colors of the lights were based on two considerations: (1) some were colors close to the standards for aviation signal colors, and (2) some were colors that would be difficult for the color-defective person to identify (National Research Council, 1981).

²⁴² AR 40-501 replaced *Army Regulation/ Flying medical fitness standards* (AR 40-110) used in the 1940s.

²⁴³ *The FDME includes a few items many physicians are unfamiliar with because they are unique. Some of these items may be performed differently between the various military services and the FAA. These tests and procedure instructions are written in the form of Aeromedical Technical Bulletins (ATB). Aeronautical Adaptability is found in the APLs and AR 40-501. Color vision testing is one of these items.*

the PIP color vision test. The plates should be shuffled periodically to avoid memorization of the testing sequence and they should be replaced every 1-2 years due to fading. Results should be recorded as Pass or Fail with the number wrong/total (ex. PASS 2/14, FAIL 3/14). The Farnsworth F2 (Tritan) plate also is administered.

If the PIP is failed, the APL color vision section gives the following recommended procedure (U.S. Army Aeromedical Activity, 2015):

The Army passing standard is PIP PASS (2 or less errors out of 14 presentations) plus passing the single F2 plate (or the PIP 2 series with eye specialist if F2 not available) (i.e., PIP series). If failing the PIP series, but passing FALANT (no errors in 9 presentations), this meets the standard, but requires an ophthalmology evaluation to define the potential color axis and specific type of deficiency as well as assess for any underlying abnormalities. Failing both the PIP series and the FALANT fails the standard. The former standard of testing color vision on the initial FDME is revised to include initial, comprehensive, and required post-mishap FDMEs.

The APL also states for any failure leading to a request for exception to policy (ETP) or waiver consideration, an aeromedical summary (AMS) is required. The AMS must include the PIP and FALANT test results, ophthalmology examination findings, and an in-flight evaluation with an ATC tower light gun (e.g., Aldis lamp) from a control tower at distances of 0.5 to 1 mile (normal traffic pattern, VFR conditions) for which 3 of 5 sequences of lights each are viewed (Figure 160). (Note: These hand-held gun lights are standard throughout military and civilian aviation. They present light signals from the tower to aircraft either on the ground or in the air, normally in response to radio malfunctions. The gun produces 6 signals using green, red, and white, in static and flashing modes (e, g., for an aircraft in flight, a steady green signal means cleared to land; a steady red signal means give way to another aircraft, continue circling; a flashing red signal means airport unsafe, do not land).



Figure 160. Hand-held ATC tower light gun.

For U.S. Army Airborne and Special Forces training, the color vision requirements are: Failure to pass the PIP set or FALANT test for color vision unless the applicant is able to identify vivid red and/or vivid green as projected by the Ophthalmological Projector or the Stereoscope, Vision Testing (SVT).

Overall, the U.S. Army's current philosophy on standards is the following: Deuteranopes and protanopes may have difficulty interpreting VASI lights' red-white color relationship. Protanopes may have difficulty interpreting red high-speed taxiway exit and runway end marker lights. At night, dichromats may be further reduced to monochromaticity when the physiological phenomenon of small field tritanopia is added; this is of relevance in distinguishing navigation and anti-collision lights. Thus, while some color vision deficiencies are acceptable, the most problematical is red-green abnormalities.

The most recent assessment of color vision tests for the U.S. Army (Walsh et al., 2016) performed 7 tests on 133 U.S. military personnel (active duty, national guard, reserve, and retired). The purpose of the study was to identify an optimal color vision test capable of accurately classify and quantify CDVs in U.S. Army soldiers.

Subjects were divided into two groups based on an optometric examination: normal color vision (n = 68) and with known congenital or acquired CVDs (n = 65). All subjects performed the same battery of color vision test on each eye separately (monocularly). The tests included: Dvorine Pseudoisochromatic Plates (PIP); Standard PIP 2 (SPP2); PIP Ishihara Compatible (PIPIC); Hardy, Rand, & Rittler (HHR) PIP, 4th Edition; Farnsworth Lantern (FALANT); Farnsworth D-15 (D15); Nagel and Oculus anomaloscopes; Colour Assessment and Diagnosis (CAD) test; and the Rabin Cone Contrast Test (CCT). All tests were administered following the manufacturer's instructions/recommendations.

The findings of the study included the following:

- There was no significance difference between the eyes on any color vision test in terms of sensitivity and specificity.
- The most sensitive test (compared to the anomaloscope) was the Dvorine PIP.
- The tests with the highest specificity were the Farnsworth D-15 and Standard PIP 2.
- The CCT demonstrated high sensitivity and specificity, whereas the CAD showed lower sensitivity and specificity.
- The D-15 demonstrated low sensitivity but optimal specificity.

The overall conclusions of the study were the current U.S. Army color vision screening tests demonstrate good sensitivity and specificity, as do the automated tests. In addition, some current PIP tests (Dvorine, PIPC), and the CCT performed no statistically worse vs. the anomaloscope with regard to sensitivity/specificity. In addition, the computer-based tests offer several advantages. These include: randomized stimuli presentation, reduced administration errors, reduced potential for memorization, or fading of printed test plates, and automated data storage (see *Testing issues* section). Based on the demonstration of high performance with the two computerized tests, the study recommended the U.S. Army implement automated color vision testing, as is being actively pursued by the other U.S. Military services.

The study also pointed out a limitation to all color vision screening tests, being “they only determine color vision function, not functional color vision.” Color vision function and functional color vision function can be looked at as separate entities. For example, an individual may fail a color vision function test (e.g., Dvorine PIP), but can functionally perform their job specialty.

U.S. Air Force (USAF).

The formation of the USAF as a separate service in 1947 culminated in the development of the American Optical PIP in 1951, with official adoption in 1953 (Tredici, Mims, & Culver, 1972; Ivan, Yates, Tredici, & Gooch, 1994). Due to a change in manufacturer this set became known as the Richmond plates in 1985. The Dvorine PIP was an allowable substitute. From 1959 through 1984, the American Optical and Dvorine 15-Plate Tests were used interchangeably and were the first tests administered for aviation candidates. These tests were not identified separately in the Federal Stock Catalogue and, therefore, when requested through supply channels, one might receive one or the other. A test failure using the plates required secondary testing using the SAM-MacBeth CTT up until 1988, when the FALANT replaced it. In 1993, the FALANT was discontinued due to its frequent failure in the detection of serious CVDs (Gibb, Gray, & Scharff, 2010). Between 1960-1964, the Nagel anomaloscope had limited use.

In 2011, the USAF issued a change to Medical Examinations and Standards (AFI 48-123), requiring the Rabin CCT for all initial flight physicals (Department of the Air Force, 2012, 2014).

U.S. Navy (USN).

Like for the U.S. Army, interest on color vision testing and standards for the USN began shortly after the English translation of *Color-Blindness in Its Relation to Accidents by Rail and Sea* became available in 1877 (Monlux, Finne, & Stephens, 2010). The first color vision standards for the USN (and Merchant Marine) was through House Resolution 135 of the Forty-Seventh Congress 1881-1883 [5], although the specific methods of testing were not stated. Likewise, the Jennings Self-Recording Color Test used by the U.S. Army was in primary use in the USN during and after WWI. Following these early years much of the color testing research and development in the USN was represented by the work of D. Farnsworth at the Naval Submarine Research Laboratory, New London, Connecticut. This work was performed during and post WWII. Developed in the 1940s, the FALANT was the major test method, designed initially to screen individuals with known CVDs in order to make up for manpower shortages in submarines (Paulson, 1966; Rings, 2013) and for testing naval signalmen (Farnsworth & Foreman, 1946a, b). It was formally adopted for Naval use in 1954 and has been used for its submarine, surface, and aviation forces since (Laxar, 1998; Sotos, 1998).

Currently, Chapter 15, Section III, Standards for Enlistment and Commissioning, the USN’s Manual of the Medical Department (MANMED), NAVMED P-117, as updated on 30 Aug 2017, states USN vision standards for enlistment, commission (officers), and entry into a program leading to a commission are different. For enlistment no color vision testing is required.

For commission, a lack of adequate color vision is disqualifying. Adequate color vision is demonstrated by:

- (1) Correctly identifying at least 10 out of 14 Pseudo-isochromatic Plates (PIP).
- (2) The Farnsworth Lantern (FALANT) or OPTEC® 900 will be authorized for commissioning qualification through 31 December 2016. Starting 1 January 2017, the FALANT/OPTEC® 900 will only be authorized for commissioning candidates who were previously accepted into a program leading to a commission utilizing the FALANT/OPTEC® 900 to demonstrate adequate color vision. A passing FALANT/OPTEC® 900 score is obtained by correctly identifying 9 out of 9 presentations on the first test series. If any incorrect identifications are made, a second consecutive series of 18 presentations is administered. On the second series, a passing score is obtained by correctly identifying 16, 17, or 18 presentations.

For entry into a program leading to a commission in the Navy unrestricted line, a lack of adequate color vision is disqualifying. Adequate color vision is demonstrated by:

- (1) Correctly identifying at least 10 out of 14 Pseudo-Isochromatic Plates (PIP). Applicants failing the PIP prior to 31 December 2016 will be tested via the FALANT or OPTEC® 900 as described below.
- (2) Passing the FALANT/OPTEC® 900 test. A passing score on the FALANT/OPTEC® 900 is obtained by correctly identifying 9 out of 9 presentations on the first test series. If any incorrect identifications are made, a second consecutive series of 18 presentations is administered. On the second series, a passing score is obtained by correctly identifying 16, 17, or 18 presentations. The FALANT and OPTEC® 900 will not be authorized for demonstrating adequate color vision starting 1 January 2017.

Section IV, Special Duty Examinations and Standards of the MANMED, NAVMED P-117, addresses aviation personnel. For consideration for any aviation duty, personnel must meet the standards for general Naval service as well as pass the color vision lantern test or PIP. Class I aviators and applicants for aviator training must meet all previous standards must pass one of the following tests:

- (1) Color vision lantern test: 9 of 9 correct on the first trial or 1 if any are missed, at least 16 of 18 correct on the combined second and third trials.²⁴⁴
- (2) PIP color plates (Any red-green screening test with at least 14 diagnostic plates; see manufacturer instructions for scoring information), randomly administered under a True Daylight Illuminator lamp: scoring plates 2-15, at least 12 of 14 correct.²⁴⁴

Class II personnel, designated and applicant Naval aircrew (rotary-wing) must meet Class I standards.

As in the other military services, the USN has recognized the need to reevaluate its color testing devices, methods, and standards, especially standards correlating with occupational color tasks (Laxar, 1998; Rings, 2013). Again, as in the other services, computer-based color vision

²⁴⁴ See NAMI Waiver Guide for validated and accepted tests.

tests are being evaluated, e.g., CAD, Rabin CCT, and WCCVT (Picken, Mann, & Rings, 2013; Rings, Gao, Reddix, Williams, & Kirkendall, 2013).

To briefly summarize U.S. military service standards for color vision, the USAF standard for pilot accession is COLOR NORMAL (no deficits found on screening), while the U.S. Army and USN standards are for COLOR SAFE, which means accepting those who may have some mild CVD, yet still passing the respective screening test algorithm (U.S. Army Aeromedical Activity, 2015).

FAA.

While this paper is focused on U.S. Army aviation issues, it will be instructive to briefly review testing and standards from the civilian perspective. For U.S. civil aviation, this begins with Louis Bauer (1888-1964) who became the first Aviation Medical Director. After graduating the Harvard School of Medicine in 1912, Bauer joined the U.S. Army Medical Corps, where he helped develop the role of the military flight surgeon and served as director of the Army's School of Aviation Medicine. Almost immediately, he undertook to define medical standards for civilian pilots and identify disqualifying conditions that could compromise a pilot's ability to operate an aircraft safely. Bauer also personally selected 57 private physicians (known now as Aviation Medical Examiners) across the country to give medical examinations for pilot licenses. In 1929, he played a leading role in organizing the Aviation Medical Association (Kraus, 2012). Bauer's medical standards required "normal" color vision of all pilots. His medical textbook noted (Watson, 2014):

"Normal colour vision is essential in a pilot because he has to distinguish landing lights on an airdrome at night; the navigation lights on other ships; an enemy plane from a friendly one; and finally the distinguishing of colour on the ground assists him in recognizing the terrain and in picking out landing places in an emergency."

The FAA has the responsibility for establishing and maintaining aviation medical requirements for civil (private and commercial) aviation in the U.S. These requirements are provided in the FAA's Guide for Medical Examiners, Application Process for Medical Certification – Examination Techniques, Item 52, Color Vision (FAA, 2015a). These requirements are applicable to pilots only; requirements for ATCs are provided in Acceptable Test Instruments for Color Vision Screenings of ATCs (ATCS 2152) FAA, 2015b).

The acceptable color vision tests, all of which are PIP tests):

- American Optical Color Vision Test (1965)
- American Optical HRR (2nd Edition)
- Richmond HRR (4th Edition)
- Dvorine (2nd Edition)
- Ishihara (14-, 24-, & 38-plate)
- Richmond, 15-plates (1983)

The FAA allows as acceptable substitutes:

- Farnsworth Lantern
- OPTEC® 900 Color Vision Tester
- Keystone® Orthoscope
- Keystone® Telebinocular
- OPTEC® 2000 Vision Tester (Must contain the 2000-010 FAR /20 feet/6 meters] color perception PIP plate to be approved)
- OPTEC® 2500
- Titmus® Vision Tester
- Titmus® I400 Vision Screener

Any tests not specially listed in are unacceptable for testing for a FAA medical certificate. Examples of unacceptable tests include, but are not limited to, the OPTEC 5000 Vision Tester (color vision portion), the Farnsworth Lantern Flashlight, yarn tests, and the AME-administered aviation Signal Light Gun test. The FAA explicitly prohibits the use of web-based color vision applications, downloaded, or printed versions of color vision tests and states examiners must use actual and specific color vision plates and testing devices for evaluations.

International aviation.

A number of international aviation organizations have developed color vision requirements or recommendations. These include the International Civil Aviation Organization (ICAO),²⁴⁵ the Joint Aviation Authorities (JAA),²⁴⁶ European Aviation Safety Agency (EASA), and NATO.

The Aeronautical Commission of the International Civil Air Navigation (the forerunner to the ICAO) established the first (although weakly worded) international civil aviation color vision standard in 1919 (Watson, 2014), stating:

“If (the pilot) is unable to distinguish pigmentary colors but is able to distinguish the coloured lights used in air navigation, (his) license may be rendered valid both for flight by night and for flight by day; If unable to distinguish either pigmentary colors or the colored lights used in air navigation, (his) license may only be rendered valid for flights by day, that is to say, for flights effected between sunrise and sunset.”

The current ICAO requirement (ICAO, 2011) did little to strengthen this standard in its statement (Werfelman, 2014): Pilots must have “the ability to perceive readily those colors the perception of which is necessary for the safe performance of duties. ”The wording of the ICAO standard, as well as the flexibility given to ICAO member states in determining exactly how they can evaluate pilots’ color vision and interpret the results, leads to “wide scope for variation in the examination and the assessment of applicants’ (color vision)” (Watson, 2014).

²⁴⁵ The International Civil Aviation Organization (ICAO) is a UN specialized agency, established by member countries in 1944 to manage the administration and governance of the Convention on International Civil Aviation (also known as Chicago Convention).

²⁴⁶ The Joint Aviation Authority (JAA) was formed in the 1970s when several of the major European National Aviation Authorities formed a union, with the objective of a cooperative safety regulatory system to achieve uniform high standards of aviation safety. The JAA standards of safety in aviation included the rules on color vision tests for pilot candidates.

In Europe, beginning in the 1970s, the JAA was considered as the counterpart to the FAA in the United States. The JAA required all applicants “to have good colour vision,” and this standard was the same for all of the JAA member states. The prevalent color vision screening test for the JAA was the Ishihara isochromatic plate test, the mostly widely accepted screening test for red-green color deficiencies. (Birch, 1997). If the initial screening was failed, then either a lantern test or the Nagel anomaloscope test could be administered but had to be taken within the JAA jurisdiction. Each State used their own preferred secondary test. As previously described, Lantern tests are vocational tests designed for aviation; many of which were designed decades ago and no longer manufactured. The three lanterns recommended by the JAA were the Holmes-Wright A (Birch, 1999), the Spectrolux, and the Beyne (Rui 1956).

In 2002, a new framework for aviation safety in Europe seeking common rules in the field of civil aviation, led to the establishment of the European Aviation Safety Agency (EASA), whose adopted rules and regulations are mandatory for each Member State. As a consequence, beginning in late 2003, JAA rulemaking activities were transferred gradually to EASA, and on 19 of March 2008, EASA took over all responsibilities which were previously in the hands of JAA. In EASA Regulation No 1178/2011 (2016), acceptable means of compliance (AMC) for color vision are:

AMC1 MED B.075 Colour vision

- (a) At revalidation, color vision should be tested on clinical indication.
- (b) The Ishihara test (24 plate version) is considered passed if the first 15 plates, presented in a random order, are identified without error.
- (c) Those failing the Ishihara test should be examined either by:
 - (1) anomaloscopy (Nagel or equivalent). This test is considered passed if the color match is trichromatic, and the matching range is 4 scale units or less; or by
 - (2) lantern testing with a Spectrolux, Beyne²⁴⁷ or Holmes-Wright lantern. This test is considered passed if the applicant passes without error.

EASA regulations do provide for a limitation allowing private pilots with varying degrees of color deficiency to exercise the privileges of their license by daytime only.

NATO, the North Atlantic Treaty Organization, also called the North Atlantic Alliance, is an intergovernmental military alliance between several North American and European states. While, testing methodology varies within NATO, all member countries employ red-green testing on initial entry flight applicants. Most repeat red-green testing over a pilot’s career. Only a few countries test for blue-yellow deficiencies either on entry or on later evaluations (Ivan, LeBail, and Daumann, 2001).

NATO color test methods include PIP tests, lanterns, cap tests, and anomaloscopes with more than 26 different tests in use (Menu et al., 2001). Most countries rely on PIP tests to establish red-green proficiency at entry, and only resort to secondary tests if the initial screening test is failed. Consequently, most all countries rely on red-green testing and do not routinely

²⁴⁷ Developed in France, the Beyne lantern has lights of five different singularly-presented colors: red, green, white, blue, and yellow.

evaluate for blue-yellow performance. However, the addition of blue-yellow testing is currently under consideration by a number of members.

The aforementioned agencies and organizations having color standards for color vision testing are only representative of a number of other national, professional, and occupational organizations that provide their own requirements, recommendations, or guidelines for color vision standards, e.g., American Society of Aerospace Medicine (ASAMS), Australian Civil Aviation Safety Authority (CASA), Civil Aviation Authority (CAA) of New Zealand, Indian Society of Aerospace Medicine (ISAM), South African Civil Aviation Authority (SACAA), Transport Canada, and UK Civil Aviation Authority (CAA).

Military color vision testing and standards: Summary.

From this review of color vision tests and standards, it is understandable how unclear the process may seem to those outside the testing community, especially to individuals who feel they are unjustly denied entry into certain job specialties. The many unofficial aviation-related forums overflow with posts by individuals who express anxiety about an upcoming or recently failed color vision test and seek an understanding or explanation of the testing process. Some even seek advice on how to undermine or circumvent the testing process.

One obvious, and major, flaw in color vision testing across both military and civilian aviation communities is the inconsistency and great variation in secondary testing methods. Internationally, it is very common for a color vision failed applicant to travel (even to another country) to seek out less stringent test method. In many instances, even in military settings, the secondary test is, in the belief of favoring job relevancy, extremely accepting of different types and severities of CVDs (Squire, Rodriguez-Carmona, Evans, & Barbur, 2005).

Testing issues.

Selecting one or more color vision tests is an important first step in ensuring validation of color vision performance and identification of CVDs. However, test selection must be followed up with care and attention given to the administration of the test(s) in order to elicit valid and reliable results (Lakowski, 1969b). Traditional color vision screening methods have numerous and well-known deficiencies including: reduced sensitivity and specificity (Birch, 1997; Miyahara, 2008; Wright et al., 2016); susceptibility to technician error and bias; frequent requirement of specialty lighting; susceptibility to cheating; and constant attention to care of test materials. The success of a testing session will depend greatly on whether these issues have been addressed.

Sensitivity and specificity.

- A number of studies have compared the array of color vision tests to the perceived anomaloscope gold standard resulting a range of ranking for sensitivity, specificity, and predictive value (Helve, 1972; Squire, Rodriguez-Carmona, Evans, & Barbur, 2005; Khan, Josi, & Pawan, 2012).

- Of the well-established tests, the Ichihara and the Farnsworth D15 consistently rank high, although with considerable variability in determined sensitivity and specificity.

Technician training.

- It is necessary individual administering the test (usually a technician) be trained in the correct procedure.
- Many color vision tests are designed for use by personnel with minimal training in color vision testing. Instructions are provided with many plate and arrangement tests; in most cases, careful reading of these instructions will provide sufficient information. Nonetheless, testing personnel must understand the purpose and importance of the test and be properly trained in its administration to ensure test validity.
- Adherence to set-up procedures, viewing conditions, and time restrictions must be followed. Testing personnel should provide a consistent, preferably written, set of instructions to subjects.
- The use of color names should be avoided (National Research Council, 1981).
- Usually not an issue in the aviation community, testing should be aware of any visual acuity deficiencies of a test subject, as the majority of color vision tests were designed for use with individuals with normal visual acuity. However, most screening tests can in fact be performed with or without glasses or contact lenses. Color testing should not be performed on subjects wearing tinted glasses or tinted contact lenses.

Viewing conditions.

- Many tests, especially those employing specific surface color require a standard illumination in relation to both relative energy distribution and intensity. Illumination type should not be assumed, but instead test instructions consulted for required or allowable substitute lighting (Hardy, Rand, & Rittler, 1946; Schmidt, 1952; Lange, Morey, & Richards, 1980; Hovis & Neumann, 1995). Historically, the MacBeth Easel lamp has been the most accepted form of illumination for most PIP tests (Figure 161) (Sell & Schwartz, 2003). This is because it is an accepted, stable approximation of afternoon, north sky, natural daylight in the Northern Hemisphere (Milburn & Mertens, 1993). While many of these lamps are in use, they are no longer being manufactured. MacBeth lamps were originally equipped with a 100-watt incandescent light bulb (General Electric part number 100A21IF) and a blue (Corning, Daylite 590) filter, which together produced a correlated color temperature of 6936 °K. Unfortunately, the original bulbs in these lamps have been replaced indiscriminately with a myriad of replacement bulbs of unknown spectral output.
- The location of the illuminating source also is important. Sources should not be placed such as to induce either direct or indirect glare.
- Increased viewing distance and shortened viewing times have been shown to increase errors (Taylor, 1983; Long et al., 1984; Long, Lyman, & Tuck, 1985; Somerfield, Long, Tuck, & Gillard, 1989).
- Usually not an issue in the aviation community, testing personnel should be aware of any visual acuity deficiencies of a test subject. While the majority of color vision tests are designed for use with individuals with normal visual acuity, most can in fact be

performed with or without glasses or contact lenses. However, subjects are not allowed to wear tinted glasses or contact lenses.



Figure 161. The MacBeth easel lamp used for many PIP color vision tests.

Care and storage of tests materials.

- With many of the most common color vision tests no longer being manufactured, it is not unusual for the tests in use to be decades old. Even with attention to the care and storage of the tests, years of handling and exposure to light will have affected performance.
- Most manufacturers' instructions caution against excessive exposure to light, moisture, and direct contact with oils of the skin. To prevent fingerprints or even great damage to the PIPs both examiner and subject should wear some type of protection for the finger.
- When not in use, test materials should be stored in a protective container.

Anti-cheating strategies

- Applicants for aviation fixed pattern of administration (versus random administration) permits the observer to become aware of the pattern
- Pages of some PIP books (especially newly printed) can be tilted back and forth so as to provide luminance clues (Nema & Nema, 2014).
- From previous testing experience or obtaining information from the internet may allow subjects to memorize correct answers based on plate number; this can be prevented by covering identifiable numbers.
- In a similar situation, previous test experience may have allowed a subject to learn the sequence of correct answers. This can be avoided by randomly reordering the presentation sequence of test images.

Color vision testing and standards: Summary.

Since the adoption of color vision performance as a physical standard over 100 years ago, various color vision tests have been developed and used by the U.S. military. While the accuracy of these tests has generally increased over time, no single test has ever reliably matched color vision deficiency with performance degradation on specific in-flight tasks.²⁴⁸ In addition, the

²⁴⁸ R. Ranaudo comments: "Older aircraft did not have the nice digital color displays we have today, and as a result, cautions (yellow), warnings (red), and normal operating (green) lights could sometimes be identified as to their meaning by simply looking at the gauge next to the light. But, the color was important in getting attention as aural warnings were very sparse. In today's cockpit, use of color is further supported by text and

lack of uniformity in acceptable test methods across the aviation community makes such a correlation more difficult (Watson, 2014).

The vast array of existing color vision tests, as well as the continuing development of new methods, has consistently eluded the attempts by vision scientists to adopt a single “one-size-fits-all” test for the determination of the type and severity of CVDs. It is possible such a single test does not exist, and a battery of tests is the most viable solution. If so, the application of a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis of the methodology of color vision testing may be useful for investigating testing across MOSs in the U.S. Army. Rogosic et al. (2012) has attempted a limited analysis for color vision testing in the maritime community. See *New and Continuing Color Issues and Future Research* section.

Although a large number of studies have looked at color in various (but specific) visual tasks (e.g., search, detection, and legibility) and some effort has been put forth to identify color vision requirements in the cockpit (MacDonald & Cole, 1988; Barbur, Rodriguez-Carmona, Evans, & Milburn, 2009), a direct correspondence of requirements to operational tasks (especially in aviation) has not been well researched. Clinical performance is still the standard metric for expected flight performance, and such an approach has been well criticized (e.g., Brookes, 2015).

Similarly, color vision standards date back to the WWI era and present the same lack of uniformity across the aviation community. A number of international organizations have attempted to address this issue but still leave specific standards (and testing techniques) to individual members. Even within the three U.S. military services, only recently has there been a call to unify methodology and standards.

Guidelines for Use of Color in Cockpit Displays

Color has been present in the cockpit for over a century. The number of colors available has increased from a handful to millions due to the advances in color-producing technologies, i.e., from dyes and paints, to filtered lamp filaments, to electron-excited phosphors (CRTs), to LCs and LEDs. In the midst of this explosion of color production has been a continuous and active effort to understand the role and utility of color in aviation. This effort has been led by vision scientists and HF researchers. Individuals working on aviation issues have centered their work on which flight tasks can most benefit from the use of color within the constraints of display design and flight environment conditions. Also important has been considerations of the impact of increased color use on equipment costs and training requirements. Not overlooked has been the concern expanded color usage may, under certain conditions, be detrimental to pilot performance and mission effectiveness (Widdel & Post, 1992; Fares & Jordan, 2015). The major goal of this effort has been to produce a set of guidelines for implementing color not just in the cockpit but in other non-aerospace applications, e.g., automobile instrument panels, industrial control panels, and website design. These guidelines have as a goal the effective use of color, which requires consideration of a number of color implementation principles (Marcus, 1995): organization, simplicity, emphasis, symbolism and interactions.

aural, which allows less reliance on color (alone) to convey urgency or malfunction. For example, a message on a MFD could be preceded by a yellow light meaning it is a caution or a red light with the appropriate aural that conveys urgency” (personal communication, November 30, 2017).

Early aviation color use research.

The red vs. white cockpit lighting issue of preserving crew dark adaptation in WWII cockpits is an example of the first efforts to study color in aviation (see *Crew station lighting* section). In the decades following, much of the research impetus was directed toward the impact of color on display-oriented search and identification performance, based primarily on the use of color coding (Christ & Teicher, 1973). Comprehensive general reviews of research investigating color use in (aviation) displays have been available from the early 1960-70s (Jones, 1962; Payne, 1964; Meister & Sullivan, 1969; Christ & Teicher, 1973); with ATC color displays having a major presence in reviews of 1980-90s research (Narborough-Hall, 1985; Reynolds, 1994; Xing, 2006c); and the explosion of color now available with AMLCDs (Snow, Jackson, Meyer, Reising, & Hopper, 1999).

While all of the reviews praised the quality of the past and recent research and its contributions to the successful integration of color into the cockpit, much of this research was criticized for being too basic, theoretical, and constrained in its approach, having focused more on fundamental human vision tasks, and not investigating the use of color in more complex, multi-tasking, real-world flight environments (Christ & Teicher, 1973). This criticism, while accurate, may have been too harsh, since human vision with all of its complexities (e.g., spatial, temporal, luminance, and color confounds) plays a major role in flight performance and must be understood. Nonetheless, with the exception of work performed in the most recent decades, much of the previous research failed to provide functional guidelines for color use.

Despite this criticism, these decades of research did produce a number of findings that form the basis of knowledge used to develop many of the guidelines for use of color currently put forth by the various factions providing recommendations to the aviation community, including designers and users (pilots). Some of the most important generalized findings of the past research are (Christ & Teicher, 1973; Krebs, Wolf, & Sandvig, 1978):

- For small, low-intensity, and briefing-occurring visual targets, the detection and recognition of target colors under both foveal and peripheral viewing conditions are limited (Connors, 1970; Siegel & Siegel, 1970).
- Detection and recognition of color varies with target location in the visual field (Kaiser, 1968; Meister & Sullivan, 1969; Connors, 1970).
- Color recognition is suppressed during voluntary saccades (Lederberg, 1970; Uchikawa & Sato, 1995).
- The hue, saturation, and value of a target and background interact to affect target perception (Barnes, 1970).
- The minimum symbol (target) size for successful color perception increases with number of colors used (Haeusing, 1976).
- The ability of an observer to discriminate detail varies with both target and background colors (Myers, 1967).
- As the number of colors used for information coding increases, user error rate and detection time increase (Shontz, Trumm, & Williams, 1971).

Early color guidelines.

Recent guidelines for the use of color provide recommendations that can be generalized across many areas of application, e.g., advertising, art, website design, and military. These newer guidelines are very HF-centric, as they should be. As is often the case, military materiel development and improvement are the impetus behind many new technologies and their implementations. Therefore, it is not surprising many of the first color guidelines were directed at military systems, with most addressing color use in the aviation cockpit. The following is an abbreviated chronological list of the more comprehensive guidelines mostly developed by or under the direction of the military services:

- 1978 – Krebs, M. J., Wolf, J. D., & Sandvig, J. H. *Color Display Design Guide*. Minneapolis, MN: Honeywell Systems and Research Center. (U.S. Office of Naval Research)
- 1985 – Narborough-Hall, C. S. Recommendations for applying colour coding to air traffic control displays. *Displays*, 6(3), 131-7.
- 1986 – Smith, S. L., & Mosier, J. N. *Guidelines for designing user interface software*. Electronic Systems Division, Air Force Systems Command Report 86-278.
- 1986 – Murch, G., & Taylor, J. *Effective Use of Color on Avionics Displays*, SAE Technical Paper 861694. Warrendale, PA: SAE International.
- 1998 – Brown, C. M. Color. In *Human-computer interface design guidelines*. Wiltshire, UK: Cromwell Press.
- 1999 – Cardosi, K., & Hannon, D. *Guidelines for use of color in ATC displays*. Washington, DC: Federal Aviation Administration.

Development of color guidelines and standards.

For the integration of color to be successful in the cockpit, it must meet the same requirements as any other information-interface mode (NASA, 2015). It must assist the user in finding, reading, and interpreting the needed information. Meeting these requirements necessitates adherence to both validated HF practices and known visual performance thresholds; and, these requirements must be met under all practical operational conditions. Assuming the integration of color is as cost effective and engineering-achievable as any competing information mode, it must transfer the needed information with at least the same level of cognitive effort.

When color displays were first introduced, the number of colors available for alphanumeric, symbols, and backgrounds was limited, making early guidelines reasonably compact. The recent rapid expansion of color technologies now has allowed the number of colors capable of being displayed to be in the millions, which demands a more wide-ranging set of DOs and DON'Ts. But, with the enviable surge of rules comes certain situations where they become

either too general or too restrictive. This makes it more difficult for system/display designers to make correct design decisions or tradeoffs (NASA, 2015).

Criticism of most recent color usage guidelines centers around three alleged major shortcomings (Xing, 2006c). The guidelines:

- Use color, visual, and HF terms unfamiliar to engineers and designers;
- Emphasize how to optimize the advantages of color use, but ignore their drawbacks or limitations; and/or
- Mostly deal with the perception of color instead of its effects on task performance.

As experience with color increased with the first fieldings of color display systems, guidelines intended to provide non-specific recommendations for rules or principles for design and usage have led to a number of standards, which assign minimum or maximum quantifiable measures to specific factors or variables. The NASA Color Usage Research Lab at the NASA Ames Research Center's, Moffett Field, CA, website has an excellent bibliography of guidelines and standards developed for both aerospace and non-aerospace applications by numerous safety, aviation, and HF organizations. (NASA Ames Research Center, 2015).²⁴⁹ These include:

- Society of Automotive Engineers (SAE) International:²⁵⁰
 - o ARP571, Flight Deck Controls and Displays for Communication and Navigation Equipment for Transport Aircraft
 - o ARP1782, Photometric and Colorimetric Measurement Procedures for Direct View CRT Displays
 - o ARP4032, Human Engineering Considerations in the Application of Color to Electronic Aircraft Displays
 - o ARP4067, Design Objectives for Electronic Displays for Part 23²⁵¹ Aircraft
 - o ARP4102, Core Document, Flight Deck Panels, Controls and Displays
 - o ARP4102/4, Flight Deck Alerting Systems
 - o ARP4102/7, Electronic Display Symbology
 - o ARP4256, Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft
 - o ARP4260, Photometric and Colorimetric Measurement Procedures for Airborne Direct View Flat Panel Displays
 - o ARD50083, Human Factors Issues Associated with Cockpit Display of Traffic Information (CDTI)
 - o AS25050, General Requirements for Colors, Aeronautical Lights and Lighting Equipment
- FAA publications:²⁵²
 - o HF-STD-001, Human Factors Design Standard, 2003. (See especially Sect. 8.6.)

²⁴⁹ Some standards may have recently updated or in-progress of revision. See respective organizational websites for most recent information.

²⁵⁰ Available from Society of Automotive Engineers International, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

²⁵¹ FAA FAR Part 23 contains airworthiness standards for normal airplanes in categories: nine or less passengers, 12,000 pounds or less; and commuter, multiengine, 19 or less passengers, 19,000 pounds or less (FAA, 2017b).

²⁵² Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591.

- o FAR Part 23, Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
 - o FAR Part 25, Airworthiness Standards: Transport Category Airplanes
 - o FAA Advisory Circular No. 25-11, Transport Category Airplane Electronic Display Systems
 - o FAA Technical Standard Order (TSO) C113, Airborne Multipurpose Electronic Displays
 - o DOT/FAA/AR-99/52 [DOT-VNTSC-FAA-98-5], Guidelines for the Use of Color in ATC Displays
 - o DOT-VNTSC-FAA-00-22, Human Factors Considerations in the Design and Evaluation of Electronic Flight Bags, Version 2
 - o DOT/FAA/AM-01/17, Human Factors Design Guidelines for Multifunction Displays
 - o DOT/FAA/OAM-TM-03-01, Multi-Function Displays: A Guide for Human Factors Evaluation
- American National Standards Institute/American Institute of Aeronautics and Astronautics (ANSI/AIAA) Publications:²⁵³
 - o ANSI/AIAA R-023A-1995, Human-Computer Interfaces for Space System Operations, 1995
- Radio Technical Commission for Aeronautics (RTCA) Publications:²⁵⁴
 - o RTCA DO-243, Guidance for Initial Implementation of Cockpit Display of Traffic Information, 1998
 - o RTCA DO-185A, Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II), 1997
 - o RTCA DO-275, Minimum Operational Performance Standards for Integrated Night Vision Imaging System Equipment, 2001
- International Organization for Standardization (ISO) Publications:²⁵⁵
 - o ISO 9241-1 Ergonomic requirements for office work with visual display terminals (VDTs) – Part 3: Visual display requirements
 - o ISO 9241-1, Ergonomic requirements for office work with visual display terminals (VDTs) – Part 8. Requirements for displayed colours
 - o ISO 13406-2, Ergonomic requirements for work with visual display terminals employing flat panel technology – Part 2: Ergonomic requirements for flat panels
- American Society for Testing and Materials (ASTM) Publications:²⁵⁶
 - o ASTM E 308-99, Standard Practice for Computing the Colors of Objects by using the CIE System

²⁵³ Available from American National Standards Institute, 1899 L Street, NW, 11th Floor, Washington, DC 20036.

²⁵⁴ Available from Radio Technical Commission for Aeronautics, 1150 18th NW, Suite 910, Washington, DC 20036.

²⁵⁵ International Organization for Standardization, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland.

²⁵⁶ Available from American Society for Testing and Materials, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959.

- o ASTM E 1455, Standard Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters
 - o ASTM E 1682-96, Standard Guide for Modeling the Colorimetric Properties of a Visual Display Unit
 - o ASTM E 1347-97, Standard Test Method for Color and Color-Difference Measurement by Tristimulus (Filter) Colorimetry
 - o ASTM E 1164-94, Standard Practice for Obtaining Spectrophotometric Data for Object-Color Evaluation
 - o ASTM D 1535-00, Standard Practice for Specifying Color by the Munsell System
 - o ASTM E 1360-90, Standard Practice for Specifying Color by using the Optical Society of America Uniform Color Scales System
 - o ASTM D 2244-93, Standard Test Method for Calculation of Color Differences from Instrumentally Measured Color Coordinates
- Other publications:
 - o ICAO Doc 9758-AN/966, Human Factors Guidelines for Air Traffic Management (ATM) Systems, First Ed., 2000, International Civil Aviation Organization.
 - o NATS Standard for the Use of Colour on Air Traffic Control Displays, 1998. Metcalfe, C., & Reynolds, L. (R&D Report 9834). London: National Air Traffic Services Ltd.
 - o MIL-STD-1787B, Military Interface Standard: Aircraft Display Symbology
 - o MIL-HDBK-87213, Military Handbook: Electronically/Optically Generated Airborne Displays
 - o AIR-STD 10/56D, Electronically and Optically Generated Displays Formats and Symbology for Fixed Wing Aircraft
 - o AIR-STD-10/72, Electronic Colour Display Systems
 - o AIR-STD-61/113/3e, Colors and Markings Used to Denote Operating Ranges of Aircraft Displays
 - o AIR-STD-61/116/6d, Human Engineering Design Criteria for the Use of Aircrew Station Controls and Displays
 - o AIR-STD-65/14B, Airfield Marking and Lighting Color Standards (ICAO Publication Annex 14, Vol. 1, App. 1, 2nd ed., July, 1995)
 - o NASA-STD-3000, Vol. 1, Man-Systems Integration Standards, Rev. B, 1995.
 - o MIL-STD-1472F, Human Engineering Design Criteria for Military Systems, Equipment, and Facilities
 - o MIL-HDBK-87213A, Military Handbook: Electronically/Optically Generated Airborne Displays

In addition to this abridged list of guidelines and standards, which includes many used by the military, there are a number of military-unique documents addressing color within aircraft. Most of these have the U.S. Army as custodian or participant activity. These include:

- MIL-C-8779, Colors, Interior, Aircraft, Requirements for; this specification establishes the color requirements for interior surfaces of Military aircraft.

- MIL-PRF-22885, Switch, Subassembly, Color Filters (for Switch, Push Button, Illuminated).
- MIL-STD-41, Aircrew Station Alerting Systems; this standard covers aircraft aircrew station alerting systems including general functions, operational logic; information content of messages; and physical characteristics of the alerting system's visual, auditory, and tactile signals.
- TOP-7-2-513, Human Factors Engineering Testing of Aircraft Cockpit Lighting Systems; this Test Operations Procedure (TOP) outlines the procedures for testing HFE aspects of cockpit lighting and the methodology involved in quantifying, qualifying, and presenting data for cockpit lighting. Cockpit lighting characteristics testing outlined in this TOP include display luminance, illuminance, contrast, balance, uniformity, sunlight readability, display color, night vision imaging system compatibility, and crew station reflections.

Recommendations.

Several abbreviated, topic-oriented lists of recommendations for the selection and use of color have been provided in previous sections, e.g., *Color aviation displays* (p. 146), *Color selection and design guidelines* (p. 163), and *Moving map displays* (p. 168). The varying scopes and perspectives of the large number of guidelines cited in this section demonstrate the difficulty in constructing a one-size-fits-all list of recommendations for integrating color into the cockpit. Yeh, Jo, Donovan, & Gabree (2013) provide one the most comprehensive lists, which is summarized in Table 16.

Applying all of these recommendations to a single component or system design is difficult and compromises are inherently required. However, there one recommendation to be strongly adhered to in the cockpit: consistency. The consistent use of color within an application and across all flight deck displays is highly desirable. There are a number of long-established color schemes and conventions for aircraft displays, e.g., the use of red and yellow-amber being typically reserved for alerting functions (warnings and cautions, respectively). Several FAA CFRs establish conventions for the use of red and amber/yellow on the flight deck (e.g., 14 CFR 23.1322, 25.1322, 27.1322, and 29.1322). If red and yellow-amber are used too broadly, pilots may become desensitized to their meaning and not be able to recognize and respond rapidly to situations where actions are time-critical. Inconsistent use of these colors can lead to difficulty interpreting their meanings when they appear, cause a slower response, and increase the potential for error (Boucek, Veitengruber, & Smith, 1977; Veitengruber, Boucek, & Smith, 1977; Widdel & Post, 1992).

Table 16. Summary of HFE-based recommendations for instrument panel color usage (adapted from Yeh, Jo, Donovan, & Gabree, 2013).

General • The colors and brightness of the display should not interfere with the readability of other flight deck instrumentation. • Colors used for attention getting and alerting should be identifiable through the full range of expected flight deck illumination levels. • Color degradation should be obvious and should not preclude the pilot from interpreting the remaining display information. • Bright, highly saturated colors should be used sparingly and only for critical and temporary information so they are not visually distracting. • Pure colors should not be used when the color/surround contrast ratio is low (e.g., blue elements on a black background) (Cardosi and Hannon, 1999). • If colors are customizable, there should be an easy way to return to a default color coding scheme (Chandra, Yeh, Riley, & Mangold, 2003). • Where multiple colors are used to enhance discrimination, the use of color shall result in no erroneous or ambiguous interpretation of the displayed information.
Use of red, amber, and yellow • Use of red, amber, and yellow must conform to the following color convention: (i) Red for warning alert indications; (ii) Amber or yellow for caution alert indications; and (iii) Any color except red or green for advisory alert indications. • Consistent use and standardization for red, amber, and yellow is required to retain the effectiveness of flight crew alert. • Use of the colors red, amber, and yellow on the flight deck for functions other than flight crew alerting must be limited.
Use of blue • The use of pure blue should not be used for important information due to low luminance on many display technologies. • Pure blue should not be used for the display of small, detailed symbols. • Blue should be avoided because of the difficulty for the human eye to focus short wavelengths. • Use of red and blue in adjacent elements should be avoided.
Consistency of colors • A common color philosophy across the flight deck is desirable. • Where appropriate, color assignment should be consistent with other color displays in the panel. • When overlaying two or more functions, using the same or similar color to convey different information is not recommended.

Additional discussion of a guideline for the number of colors to be used beyond that in in Table 16 (for color coding) in the presentation of information (including displays and maps) is warranted. In 1956, cognitive psychologist George Miller published a seminal paper on short-term memory, “The magical number seven, plus or minus two: Some limits on our capacity for information processing.”²⁵⁷ Since, everything from the number of colors used on a map to the number of bullet points listed on a Microsoft® PowerPoint slide has been recommended to be limited to no more than 7. In many cases, these limits are an inappropriate application of Miller’s findings, as his work involved the ability of subjects to remember a sequence of unrelated pieces

²⁵⁷ In the science of psychology, this is known as Miller’s Law, the observation that the number of objects an average person can hold in working memory is about seven.

(chunks)²⁵⁸ of information all at once. The term *memory span* is used to refer to the longest list of chunks (e.g., numbers, letters, and words) a person can repeat back in correct order after presentation (50% of the time).

Table 16 (continued). Summary of HFE-based recommendations for instrument panel color usage (adapted from Yeh, Jo, Donovan, & Gabree, 2013).

Color coding • Aviation conventions should be observed when using colors for coding. • When colors are assigned a meaning, each color should have only one meaning. • No more than six colors should be used for color coding on the display. • The color of controls should be black or gray (McAnulty, 1995). • Colors should minimize display interpretation errors. • If color is used for coding task-essential information, use at least one other distinctive coding parameter (e.g., size, shape, label). • The following color pairs should be avoided: saturated red and blue, saturated red and green, saturated blue and green, saturated yellow and green, yellow on purple, yellow on green, yellow on white, magenta on green, magenta on black, green on white, blue on black, and red on black.
Color redundancy • Color-coded information should be accompanied by another distinguishing characteristic such as shape, location, or text (label).
Color discriminability • Displays shall be readable and colors shall be discernable under anticipated lighting conditions. • Requiring the flight crew to discriminate between shades of the same color for distinct meaning is not recommended. • Adjacent colors should not be equal in luminance when discrimination of edges or detail is important. • Displayed information shall have sufficient luminance contrast and/or color difference to discriminate between the following: (i) Between symbols (including characters and/or lines) and the background (ambient or generated) on which they are overlaid; (ii) Between various symbols, characters and lines, including when elements overlay ambient or generated backgrounds; (iii) Between the generated backgrounds and ambient backgrounds; and (iv) Between the generated backgrounds of various specified colors.
Background color • A background color (e.g., gray) should not impair the overlaid information elements. • If texturing is used to create a background, it should not result in loss of readability of the overlaid symbols nor should it increase visual clutter or pilot access time.

Miller, himself, was using the phrase “magical number seven” in a exaggerated manner. More recent short-term memory research has confirmed a capacity limit but has not produced a “magical” number. Some studies have shown the human memory span to be around seven for digits, around six for letters, and around five for words (Shiffrin & Nosofsky, 1994). Other

²⁵⁸ The term *chunk* is used in the study of short-term memory and is defined as a collection of elements strongly associated with each other but weakly associated with elements of another chunk (Gobet et al., 2001).

studies have suggested the capacity limit is only three to five chunks, depending on observation conditions (Cowan, 2001).

For the question of a maximum number of colors to be used on a display, the more general question is whether there is a fixed total amount of visual information that can be stored in visual short-term memory (Alvarez & Cavanagh, 2004). The term “visual information” refers to the visual features or details of an object that are encoded and stored in memory, not to information in the mathematical sense of information theory (Shannon, 1948). Therefore, the total visual information load associated with a particular object corresponds to the amount of visual detail (i.e., number of features) stored for the object.

Color is just one feature (or dimension) of a visual object; other possible features include size, texture, and orientation. More recent research (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) has shown visual short-term memory appears to be limited by the number of objects that can be stored, independent of the number of features for each object. Studies by Alvarez & Cavanagh (2004) showed that in terms of the number of objects, visual short-term memory capacity varies across different types of objects. Subjects were able to remember more of some objects, such as colored squares, than of other objects, such as Chinese characters or random polygons. This variation in the number of objects that can be stored implies capacity is not fixed exclusively to the number of objects. Additionally, there appears to be an inverse relationship between the information load per object and the number of objects that can be stored. This suggests there is an upper bound on storage set in terms of the total amount of information. More capacity is required for more complex objects; consequently, there is a trade-off between the complexity and the total number of objects that can be stored in short-term memory. This means there is no “magical” number for the maximum number of colors for a display. Instead, there are most likely differing number of colors limitations, based on the application (i.e., the objects or elements being presented for viewing).

It has been pointed out previously that many guidelines are generalized. The list in Table 16 contains many such generalities. This may be unavoidable when guidelines attempt to address every application involving color. Some of guidelines in the Table 16 strive to recognize the dynamic and complex aviation environment (e.g., illumination levels that include such extremes as glare and low-level lighting). However, many ignore individual user differences (e.g., age, presence of CVDs, and culture). Fortunately, several studies investigating color schemes used for cautions and warnings have found general similarities in the effectiveness of certain colors (i.e., red, yellow, black, and orange) across some multi-language groups of pilots (Wogalter, Frederick, Herrera, & Magurno, 1997; Smith-Jackson & Wogalter, 2000).

Color in U.S. Army Rotary-Wing Crew Stations

The first presence of color in Army cockpits was most likely in the bandanas worn by the first pilots. Today color is used extensively in the cockpit to provide important information about aircraft flight status and is (unintentionally) present in pilotage imagery that allows the pilot to fly at night. Used first as a frivolous sign of bravery, color in modern aviation is a serious subject.

Today, Army aviation primarily consists of rotary-wing aircraft (helicopters), but it had its roots in the bi-planes of Wilbur and Orville Wright fame. The advancement of Army aviation and its transition from fixed-wing to rotary-wing aircraft is the result of half a century of inter- and intra-service rivalries and the unique aviation capabilities provided by helicopters. The first aeromedical issue relating to color use in Army aviation arose as the Army began to seriously implement night flight operations in WWII. The issue was which color of cockpit lighting (i.e., red vs. white) should be used in order for pilots to maintain their dark adaptation (see *Crew station lighting* section). Once the unique advantages of helicopters over fixed-wing aircraft became obvious (e.g., ability to operate in confined areas and perform search and rescue [SAR] and medical evacuation [MEDEVAC] missions over water and in rugged terrain), night imaging technologies were explored and fielded, which greatly enhanced night operation capabilities. The night vision pilotage imagery was, and still is, monochromic, although color imagery is on the horizon.

Night Combat and the Ascent of Helicopters in Army Aviation

The U.S. Army has long recognized the effectiveness of extending combat operations into the hours of darkness and periods of low illumination, e.g., fog, rain, and snowstorms (Norris, 1985). One of the central issues facing warfighters in night operations is visibility. Historically, night ground-warfare and troop movements were strongly impacted by available levels of naturally provided lighting, e.g., starlight and moonlight. In WWI, German soldiers used torches, lamps, and coal and sulfur-based flamethrowers²⁵⁹ to illuminate night fighting. Based on the development of electron image tubes in the 1930s, IR night vision devices became available at the onset of WWII (Armasight, 2015). These included a number of anti-tank imaging systems used in tandem with IR headlamps. By the latter part of WWII (c. 1943-44), T3 Carbines were being fitted with M2 IR sniper scopes (Figure 162, left). Although issued in limited numbers, these night vision-equipped infantry weapons proved to be highly effective in the U.S. Okinawa campaign in the Pacific theater. The 1950s and early 1960s saw continuous improvement in *active*²⁶⁰ night vision sights. However, by the late-1960s, *passive* night vision devices, such as the Army/Navy Portable Visual Search (AN/PVS-1) Night Vision sight “Starlight” scope, were being fielded on the M14 rifle (Figure 162, right). These devices operated using only the ambient light from the moon, stars, and sky glow. By the 1980s, sniper night sights, thermal night imaging equipment, and I² night vision devices were vastly improving the U.S. Army’s offensive ground capabilities (Williams, 1984).

²⁵⁹ While the concept of the flamethrower dates to as early as the 5th century, Germany introduced its use into modern warfare in 1914 via two models of a flamethrower or *Flammenwerfer* (Duffy, 2009).

²⁶⁰ Night vision systems can be classified as *active* or *passive*. Active devices (often referred to as Generation 0) require an IR source (or illuminator) that projects a beam of near-IR light. Invisible to the naked eye, this beam reflects off objects and bounces back to be collected by the objective lens of the night vision device. In passive devices (Generation 1 and higher), ambient light provided by the moon and stars, which augments the normal reflected IR in the environment, is collected by the objective lens of the night vision device; they do not require an active source.

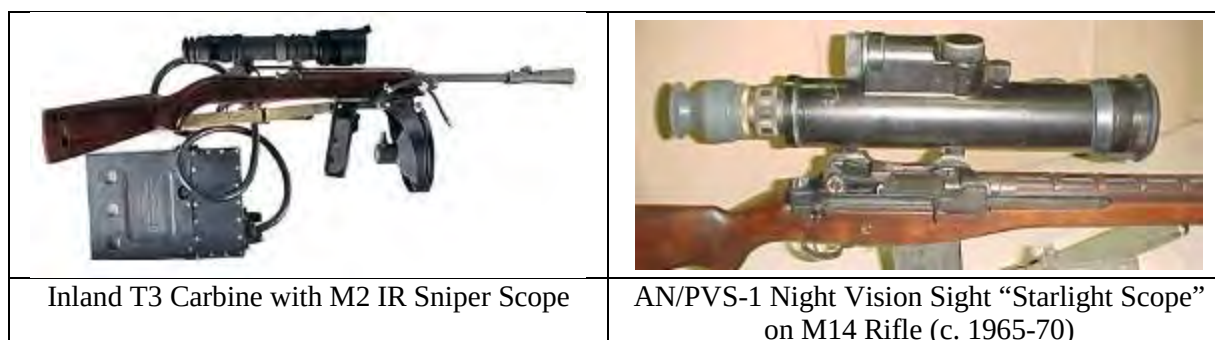


Figure 162. Night fighting weapons: Inland T3 Carbine with M2 IR Sniper Scope (left) and AN/PVS-1 Night Vision Sight "Starlight Scope" on M14 Rifle (right).

For U.S. Army aviation, the first recorded night flight is credited to aviation pioneer Wilbur Wright and U.S. Army 2LT Frederick Humphreys.²⁶¹ The flight occurred on October 22, 1909 and consisted of 42 minutes of orbiting over College Park, MD, "under a bright moonlight" (Fischer, 1998; McFarland, 1998). The U.S. Army expressed a definite interest in these new, heavier-than-air aircraft, and the potential of the airplane as a military weapon was being recognized. However, U.S. industry was not yet capable of producing the number of aircraft needed for entry into WWI. In 1914 the U.S. Army's Aviation Section of the Signal Corps had only five air squadrons, with three others being formed. By April 6, 1917, when the U.S. declared war on Germany, it had only 56 pilots and less than 250 aircraft (all obsolete). French Premier Alexandre Ribot had told President Woodrow Wilson the Allies would need an American air force of 4,500 aircraft and 5,000 pilots by 1918 in order to achieve victory (McFarland, 1998). A U.S. aircraft manufacturing industry as we know it today was virtually nonexistent at the beginning of WWI. So, it is not surprising that when the war ended in November 1918, only one aircraft type had seen action for the U.S. on the front lines, the De Havilland (Airco) DH-4 light/reconnaissance bomber (Williams, 2005).²⁶²

Even though France, England, and Germany had demonstrated how important aviation assets could be in military conflicts, the 1920s-1930s saw the U.S. demonstrating little interest in pursuing this technology or in the development of a separate aviation branch of the military. Nonetheless, persistent efforts by early aviation pioneers, such as James (Jimmy) Doolittle and Billy Mitchell, slowly led to the recognition of aviation as a vital defensive and offensive capability, paving the way for the establishment of the United States Army Air Corps (USAAC) in 1926, then as the U.S. Army Air Forces on June 20, 1941 (just 5½ months before U.S. entry into WWII), and finally splintering to form a separate War Department branch (the U.S. Air Force [USAF]) in September 1947.

U.S. entry into WWII again found the Air Corp understaffed and underequipped. When Germany invaded Poland in September 1939, the Air Corp consisted of approximately 2,000 pilots and 400 combat aircraft. Following an aggressive training program, the (then) USAAF graduated 193,400 pilots from 1939 to 1945; and nearly 300,000 aircraft had been manufactured

²⁶¹ Charles K. Hamilton, an American stunt pilot who flew with the Curtiss Exhibition Team, also is credited with the first night flight in America, in Nashville, TN, in August, 1910 (Parks, 2012; Williams, 2005); however, this most likely refers to non-military aviation.

²⁶² An excellent history of U.S. Army aviation can be found in Williams, J. W. (2005). *A history of Army aviation: From its beginnings to the war on terror*. New York: iUniverse, Inc.

by the end of the war (Herman, 2012). The overwhelming majority of these were fixed-wing aircraft, e.g., bombers, fighters, reconnaissance, and transports. However, as early as 1921, the Air Corp was exploring rotary-wing aircraft, i.e., helicopters (Williams, 2005). However, it would not be until late 1941 before the Army would acquire its first mass-produced, operational helicopter, the Sikorsky YR-4.²⁶³ The first U.S. Army combat use of helicopters was in Burma in 1943 where the Sikorsky YR/R-4 was employed primarily for SAR and MEDEVAC. While helicopters saw limited deployment during WWII and had little impact on the progress and outcome, they demonstrated a proven value for light transport, rescue, and lifesaving (Williams, 2005; Treloar, 2013).

The U.S. Army's recognition of the capabilities of helicopters increased with their role in Korea (1951-1953) and Vietnam (1961-1975). In Korea, Army helicopters began flying SAR and MEDEVAC missions in early 1951. Another critical role was the delivery of food and ammunition. In addition, it quickly became obvious helicopters were a valuable command-and-control aid due to their ability to operate in Korea's mountainous terrain that hindered communication between command staff and deployed units (Kreisher, 2011). Helicopters flown in the Korean Conflict included the Bell H-13 Sioux (Light Utility/Observation), the Bell Model 47 (MEDEVAC and observation), the Hiller OH-23 Raven (light utility and observation), and the Sikorsky H-19 Chickasaw (multipurpose transport).

In the Korean conflict, helicopters officially were not certified for night flying. But with so many lives at stake, pilots frequently defied the ban on night flying and conducted hundreds of dangerous nighttime MEDEVAC missions (Kreisher, 2011). Helicopters had no lighted instrument panels, so night flights were performed with flashlights secured between the pilots' legs (Sandler, 1995).

It was the Korean Conflict that proved the value of helicopters; however, it was during the Vietnam War that helicopters were relied upon to perform not just their previously identified essential roles of troop and cargo transportation, SAR, and MEDEVAC, but also to serve as gunships and airborne command centers. It was this enormously expanded list of capabilities "that made the helicopter the ubiquitous symbol of the war in Vietnam" (Treloar, 2013). The Piasecki H/CH-21 Workhorse/Shawnee (cargo, MEDEVAC and troop carrier) was the first U.S. helicopter deployed in Vietnam (in 1961). However, it was the Bell UH-1 Iroquois' (unofficially nicknamed the "Huey") (Figure 163, left) arrival in 1962 that raised the helicopter to its iconic role and shaped the future of Army aviation. The UH-1 served in every role from SAR and MEDEVAC to troop carrier and troop deployment. A number of UH-1 helicopters were outfitted armaments that included various combinations of M60 machine guns, 2.75" rocket pods, 7.62 mm machine guns, thereby expanding their role to that of gunship.

It was in Vietnam in 1967 that the world's first production attack helicopter, the Bell AH-1 Huey Cobra (Figure 163, right), made its debut. Among its combat roles the Cobra provided fire support for ground forces, escorted transport helicopters, and formed "hunter killer" teams by pairing with OH-6A scout helicopters (Bishop, 2006; CombatAircraft.com, 2016).

²⁶³ The Sikorsky YR/R-4 was a two-seat helicopter designed by Igor Sikorsky with a single, three-bladed main rotor and powered by a radial engine (https://en.wikipedia.org/wiki/Sikorsky_YR-4).



Figure 163. The UH-1 Iroquois (Huey) (left) and AH-1 Cobra attack helicopter (right)

Night imaging technology in Army aviation.

The use of night imaging technology has been driven by the Army's ever-expanding mission and subsequent nighttime operational needs (Heinecke, Rash, Ranaudo, & Hiatt, 2008). Two night imaging technologies have been explored and implemented in Army helicopters: thermal imaging (i.e., forward-looking infrared [FLIR]) and image intensification (I^2). The physics of these two technologies are different; therefore their benefits and limitations also differ. I^2 sensors operate on the principle of light amplification, and their performance is a function of the level of ambient illumination. FLIR sensors operate on temperature differences between adjacent objects or regions. FLIR sensors do not require visible illumination. Their performance is a function of the ambient temperature gradient.

FLIR.

FLIR thermal sensors can be designed to “see” radiation in either the 3 to 5- μm or 8 to 12- μm (10^{-6} meters) spectral range. All objects radiate measurable amounts of energy in these spectral ranges. These ranges are dictated by the IR transmittance windows of the atmosphere. The amount of radiated energy is dependent on temperature and type of material. Thermal imaging is used for both pilotage and targeting on the U.S. Army's AH-64 Apache attack helicopter. The targeting sensor system is known as the Target Acquisition and Designation System (TADS)²⁶⁴ and the pilotage sensor system is known as the Pilot Night Vision System (PNVS). The PNVS provides imagery to the IHADSS HMD (Figure 1, p. 2, bottom, right). Both the TADS and the PNVS thermal imaging sensors are mounted on the nose of the aircraft (Figure 164) and operate in the 8-12 μm spectral range (Figure 165).

The color of the PNVS FLIR imagery is defined by the spectral output of the IHADSS's miniature CRT (Figure 15, p. 32, left). This CRT uses a monochromatic yellow-green phosphor, P-43, having a peak emission at approximately 543 nm. This wavelength is extremely close to 555 nm, the peak sensitivity of the average human eye under daylight conditions (photopic vision) as defined by the CIE spectral luminous efficiency function (Gegenfurtner & Sharpe, 1999). Consequently, green light at this wavelength produces the impression of highest brightness when compared to light at other wavelengths (Michel, 1995). An example of the

²⁶⁴ By 2003, the original TADS had been updated across the Apache fleet with the Modernized Target Acquisition and Designation System (M-TADS).

IHADSS P-43 phosphor-generated FLIR pilotage imagery (with symbology overlay) is presented in Figure 166.



Figure 164. The nose-mounted PNVS and TADS FLIR sensors on the AH-64 Apache helicopter.

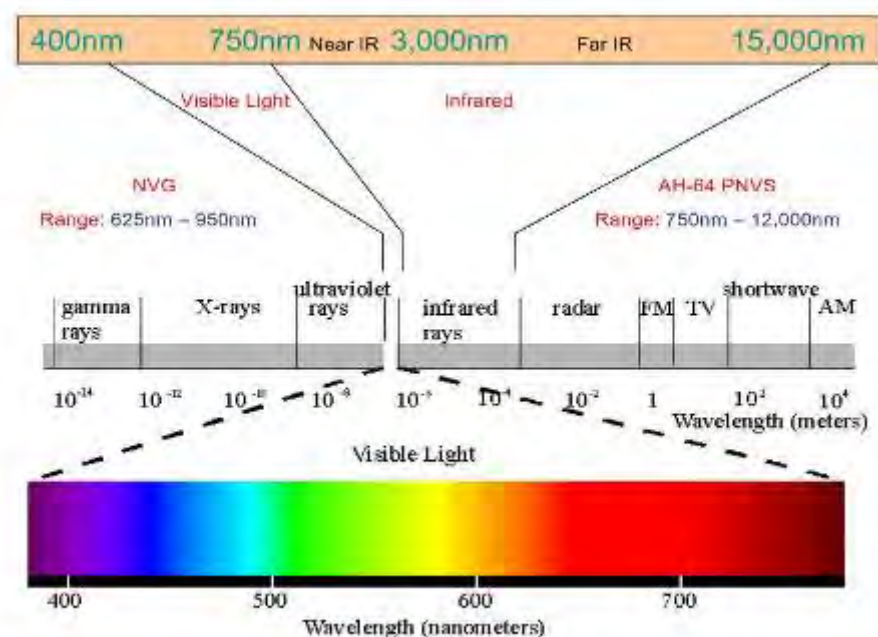


Figure 165. Electromagnetic spectrum showing spectral operating ranges for the I²-based ANVIS/NVG and AH-64 PNVS night imaging systems (Department of the Army, 1988).

Currently under development by Lockheed Martin Corporation, Bethesda, MD, for the AH-64 Apache is a system designated as the Modernized Day Sensor Assembly (M-DSA). This new technology includes an upgraded near-infrared (NIR) and visible color sensor that allows Apache pilots to see high-resolution, high-definition NIR and color imagery on cockpit displays (Lockheed Martin Corporation, 2015). It upgrades the Modernized Target Acquisition Designation Sight/Pilot Night Vision System (M-TADS/PNVS) on the AH-64E Apache helicopter, delivering multi-color imagery to the cockpit (DefenseWorld.net, 2016). The M-DSA is expected to be fielded first on the E-model Apache (AH-64E) in 2019.



Figure 166. IHADSS yellow-green P-43 phosphor generated FLIR pilotage imagery with symbology overlay (enhanced photograph).

I².

As with FLIR sensors, I^2 devices are totally passive in operation. They are based on the principle of light (actually electron) amplification. These devices intensify (amplify) reflected or emitted light in order for the human eye to more easily in poorly illuminated (low-light) scenarios. The usability of the resulting intensified image depends on the “intensification (amplification) factor” of the I^2 device and the level of available light. It is important to note I^2 devices cannot see in total darkness; there must be some minimum level of light present, although the latest generation I^2 tubes can operate extremely well under starlight conditions.

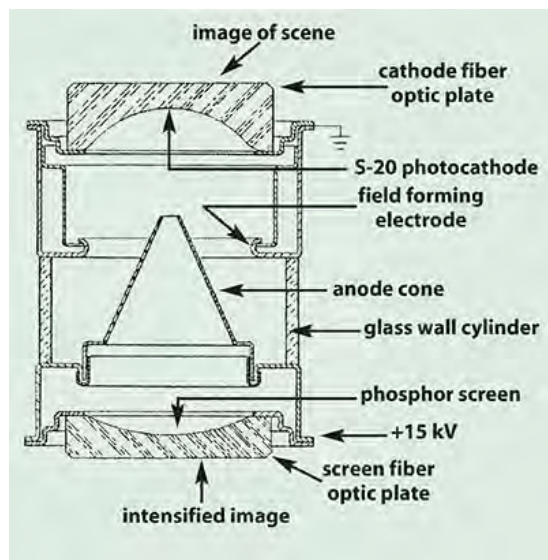


Figure 167. Basic operating principle of I^2 tube (1st generation).

The basic principle of image intensification, as was in 1st generation (GEN I) I² tubes, is the scene being viewed is focused on a photosensitive material, known as the photocathode (Figure 167). The photocathode surface emits electrons proportional to the amount of light striking it from each point in the scene. The emitted electrons are accelerated from the photocathode toward a phosphor screen by an electric field. The light emerging from the phosphor screen is proportional to the number and velocity of the electrons striking it at each point. The observer views the intensified image formed on the phosphor screen through an eyepiece (Verona, 1985; McLean, Rash, McIntire, Braithwaite, & Mora, 1997).

The 1st generation I² devices were introduced into military use in the mid-1960s during the Vietnam campaign and were used by infantry for night observation/reconnaissance missions. The first I² device used in U.S. Army aviation was a modified version of the ground system introduced in 1973 but with 2nd generation I² tubes. This system was known as the AN/PVS-5²⁶⁵ series NVG. Since 1973, several models of the basic AN/PVS-5 NVG have been fielded: the basic AN/PVS-5 and three modified versions. While the models differed in one or more ways, they all used 2nd generation (GEN II) tubes. A significant improvement was the use of a microchannel plate (MCP), a solid-state amplifier originally produced in the 1960s (Schmickley, 2001) (Figure 168).

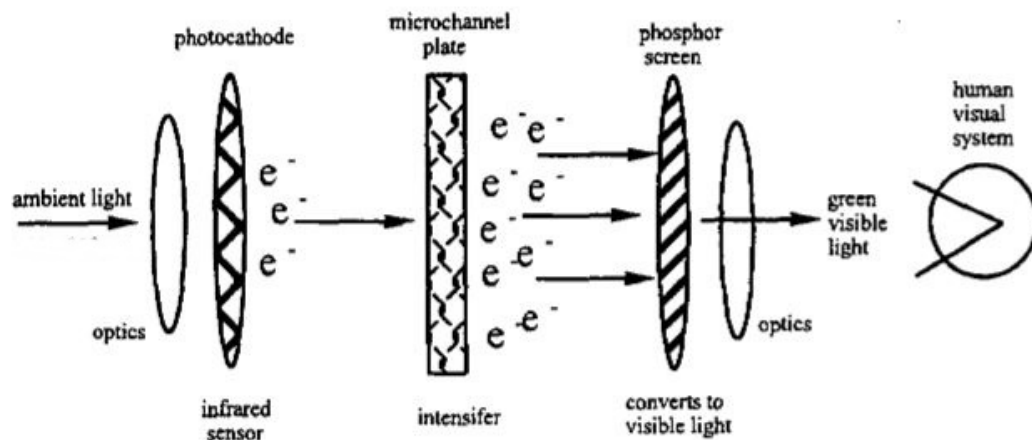


Figure 168. Basic operating principle of I² tube (2nd generation) using microchannel plate for electron amplification.

The operation of 2nd generation I² devices is similar to 1st generation devices. When a focused photon is incident on the device, it strikes the photosensitive photocathode. This results in the emission of an electron, which then is drawn by an electric field through the MCP. Composed of a thin wafer of tiny glass tubes whose walls are coated with an emissive material, the MCP produces additional electrons in a cascading effect. As these electrons leave the MCP, they strike the phosphor screen, with each electron producing a photon that is seen through the eyepiece (Figure 169). While it is actually electrons being multiplied inside the tube, effectively for every one photon that strikes the photocathode, there are thousands that are produced and

²⁶⁵ This nomenclature derives from the following: the “AN” stood for Army or Navy application, “P” meant portable, “V” signified visual, and “s” indicated detecting or range bearing (van Lundutt, 1986).

eventually strike the phosphor screen; hence, the designation of I^2 devices (e.g., ANVIS) as light amplification devices.²⁶⁶

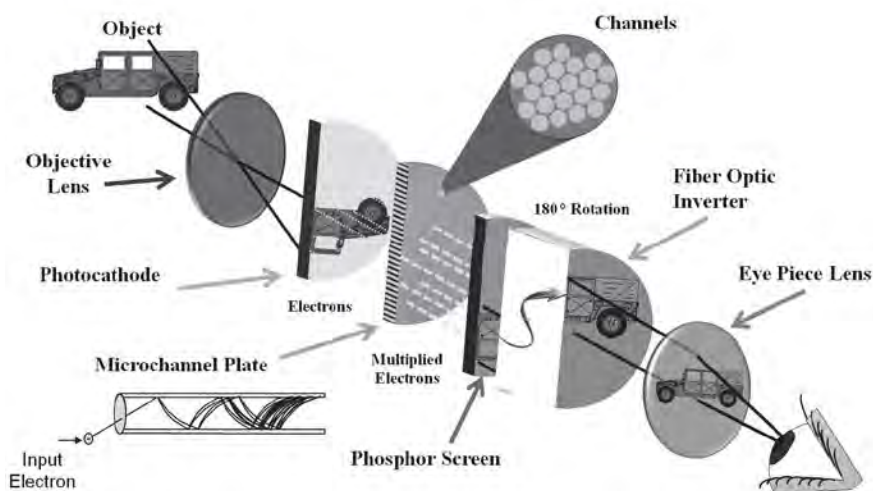


Figure 169. I^2 tube (2nd and 3rd generation ANVIS) with microchannel plate.

Although the first operational tests were in 1982, it was not until 1989 that 3rd generation (GEN III)²⁶⁷ tubes began to make their appearance. They were the foundation of a new night vision I^2 system designed especially for aviation. This system was known as the AN/AVS-6 Aviator's Night Vision Imaging System (ANVIS) (Figure 170). They operate over a spectral range of approximately 625-950 nm (Figure 171).

Versions of ANVIS are designated Class A, B, or C, depending on total system response, which is defined by the type of coating or "filter" applied to the objective during the manufacturing process. The purpose of the filter is to block certain frequencies of light, preventing the illumination from cockpit and instrument lights from affecting performance. Class A ANVIS came first. As cockpit lighting and instrumentation evolved beyond blue-green flood lighting and chem sticks²⁶⁸ to include color MFDs, Class B filters were adopted by the other military aviation services and the civilian sector. Collectively, these filters are referred to as "minus-blue" filters. These differing filters are related to the concept of "ANVIS-compatible" lighting, which has been mentioned in several sections and will now be discussed with respect to ANVIS Classes (see also the *Crew station lighting* section).

An important limitation of ANVIS is their inability to discriminate between light originating from the external world and light originating inside the cockpit. ANVIS have an "automatic gain control (AGC)," which reacts to the ambient environmental and cultural light level by decreasing the multiplication or gain factor when the ambient light level increases above approximately the equivalent of a quarter moon illumination. As a result, if light sources in the

²⁶⁶ The amplification factor discussed here is usually referred to as the tube gain (~40,000 for GEN III tubes); it should not be confused with *system gain*, a more useful factor that describes total system performance (a measure of how many times brighter a scene is in the NVG image when compared to being viewed with the naked [unaided] eyes).

²⁶⁷ Progression from 1st to 3rd generation tubes primarily involved improved light sensitivity.

²⁶⁸ Also known as glow sticks, *chem sticks* are self-contained, short-term light-sources. They produce light through chemiluminescence.

cockpit can be “seen” within the ANVIS field-of-view, then the AGC may reduce the system gain if the lighting is not compatible. This results in a system gain not optimized for the external illumination level, usually reducing the pilot’s night vision flight capability. The applied filters are designed to prevent cockpit lighting from reducing this capability. The original ANVIS Class A filter has a 50% cutoff at 625 nm, which means energy below (shorter wavelengths than) 625 nm is prevented from entering the I² tubes. With this filter, wavelengths other than blues and greens (e.g., yellow, orange, red) will pass through the filter and enter the intensification process. The U.S. Army exclusively uses Class A filters.



Figure 170. The AN/AVS-6 Aviator’s Night Vision Imaging System (ANVIS).

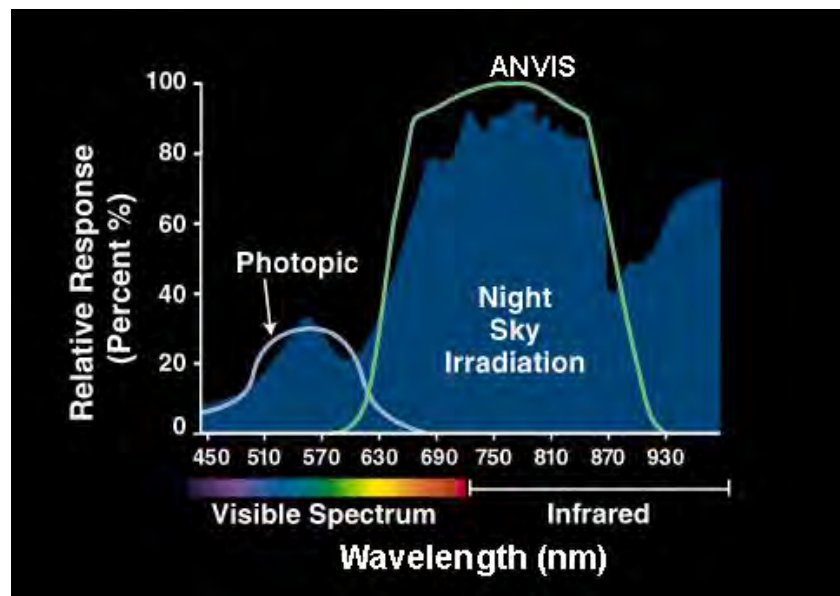


Figure 171. The eye’s (photopic) and ANVIS spectral responses as compared against the night sky’s irradiance.

To allow more colors to be used in the cockpit (an important consideration with the increased use of color displays), a Class B filter was developed that blocks light energy below 665 nm. This allows more yellows and orange-reds to be used in the cockpit lighting design without significantly affecting the intensified image. However, sensitivity to the outside visual scene is reduced by about 8-10% in moonless conditions. Later a notch or pass-band filter was added to the Class B filter, which allows approximately 1% of the green light energy around 550 nm (green) to enter the intensification process. This is a Class C filter (also known as Modified Class B or Leaky Green filter) (Aldous & Luke, 2011) and was developed so pilots would be able to see fixed HUD display symbology as well as ANVIS imagery.

This dilemma has driven cockpit lighting designs, requiring designs that allows for internal viewing of instruments but will not artificially lower ANVIS performance (Rash & Manning, 2003). Such lighting is referred to as “ANVIS-compatible” lighting (see *Exterior lighting for U.S. Army aircraft*, *Interior lighting*, and *Current U.S. Army Cockpits* sections).

While internal I² tube performance has improved immensely since their introduction, there hasn't been any change in the outward physical appearance of the ANVIS since the early 1990s. Changes from the original ANVIS include 25-mm eyepieces, independent interpupillary distance (IPD) adjustments, fine-focus 4-lobe objective lenses, and increased fore/aft range adjustment range.

The primary color issue with these devices is the display on the eye end of the AN/PVS-5 and ANVIS, which includes a phosphor screen. The AN/PVS-5 initially used the P-20 phosphor. P-20 is green, relatively narrow band (100 nm), and has a peak at 530 nm. Due to a noise problem (related to the low cathode sensitivity of the 2nd generation tubes), the P-20 was replaced with a RCA F2 126-type 1052 phosphor. This replacement was similar to the P-20 in that it was yellow-green and peaked close to 530 nm. This phosphor also had a slower persistence²⁶⁹ than the P-20. ANVIS has used P-20 and P-22 phosphors (both green in color with peaks near 530 nm). However, eventually the ANVIS display was switched to the P-43 phosphor. P-43 also is yellow-green in color but is extremely narrow band (5 nm) and peaks at 543 nm. An example of current I² imagery is shown in Figure 172).

The persistence (10%) of P-43 is 1.2 milliseconds, making it a medium-short persistence phosphor. P-43 is the phosphor used in the miniature cathode ray tubes in AH-64 Apache's IHADSS. A 1996 study found little difference in performance of the P-43 over the P-20 and P-22 (Rabin, & McLean, 1996). In addition, the narrower band P-43 produces less chromatic aberration (but does have blue, orange, and red emission side-bands). However, the monochromaticity of the P-43 phosphor has caused some visual complaints from pilots (see *Monochromatic imagery* section).

²⁶⁹ The persistence of a phosphor is defined here as the time required for a phosphor's luminance output to fall to 10% of maximum.



Figure 172. Representative I² P-43 imagery.

ANVIS offers pilots an enhanced capability to operate at night and in other periods of low illumination. However, there are limitations other than cockpit lighting imposed by the system on pilot vision. These include reduced FOV (40° circular), reduced resolution at some illumination levels, reduced depth perception, reduced dark adaptation, and, of course, loss of true-color information due to the narrow-band imagery.

It is not surprising full-color ANVIS is on the wish list for pilots. Industry has worked on this potential, and a few systems have been developed as prototypes. One example is the Color Capable Night Vision Device (CCNVD), a complex system of rotating filters and optical amplifiers being investigated to assist individuals with CVDs. However, this system would have difficulty meeting flight-worthiness requirements. Another system for displaying nighttime imagery with natural colors fuses two spectral bands, IR and visible, to enhance night vision imagery. The fused image offers more detail than either of the input sensors alone, but often has an unnatural color appearance (Qadir, 2013). This problem has been attempted to be resolved via color look-up tables.

An inherent perceptual problem with color I² systems is they detect most of their energy in the IR spectrum, which does not correspond with real-world color. Systems that attempt to colorize I² imagery must rely on false or pseudo color. However, there is no lack of attempts to use sensor fusion to achieve “natural color” (Toet, 2003; Gu, Sun, & Fang, 2008; Hogervorst & Toet, 2010).

Integration of Color Displays into U.S. Army Cockpits

The USAF has led the U.S. services in the integration of color displays into the cockpit. They demonstrated the first use of color CRTs in the 1970s (Patzner, 1996) but initially decided against its use due to technology’s inadequacy in available luminance and contrast. The USN came to a similar conclusion in the late 1970s (Stokes & Wickens, 1988). Both services would eventually field color CRTs in a limited scope. Then, the USAF would be responsible for the

introduction of AMLCDs in the mid-1980s, bringing full color to wide-spread use in U.S. military cockpits (Snow, Jackson, Meyer, Reising, & Hopper, 1999; Hopper, 2000).

The Army's first use of color MFDs in a fielded glass cockpit design was in the OH-58D Kiowa introduced in 1987. A similar crew station design for the MH-60K Blackhawk entered service in 1994, followed by the MH-47E Chinook also in 1994, and the AH-64D Apache in 1997. The cancelled 1990's RAH-66 Comanche program was totally committed to the full-color glass cockpit configuration and the advanced digital technology such a design could support. This was part of the growing focus on the "digital battlefield."

Current U.S. Army Cockpits

The U.S. Army currently fields three operational rotary-wing aircraft (helicopters) (Figure 173): the Sikorsky UH-60 Blackhawk (top), the Boeing CH-47 Chinook (middle), and the Boeing AH-64 Apache (bottom). All three of these aircraft types have models with modernized "glass cockpits" based on MFDs: UH-60M, CH-47F, and AH-64D, respectively.

UH-60M Blackhawk crew station.

The UH-60 Blackhawk is a four-bladed, twin-engine, utility helicopter. Its roles include tactical troop transport, MEDEVAC, and both internal and external (sling) cargo transport. The aircraft's fuselage is divided into two compartments, the cockpit and cabin. The pilots sit in parallel, each with a set of flight controls and instruments (Department of the Army, 2009).

First fielded in 1979, the latest models are the UH-60L and UH-60M. The UH-60M cockpit (Figures 174 and 175) has an open architecture design, the Common Avionics Architecture System (CAAS),²⁷⁰ and incorporates an array of color displays, including four MFDs featuring high resolution, ANVIS-compatible, sunlight readable, 6 by 8-inch AMLCDs. These MFDs can be configured either as a PFD or a digital moving map. Two CDUs (consisting of AMLCDs), which present mission and flight planning data and communication/navigation (COM/NAV) information via a full alphanumeric keyboard, are mounted in the center console (Department of the Army, 2009).

The UH-60M interior lighting system consists of cockpit dome lights and utility lights. ANVIS (NVG) blue-green or white lighting can be selected for the cockpit dome and utility lights. The ANVIS lighting consists of interior blue-green lighting. Two blue-green and two white cockpit floodlights provide secondary lighting for the cockpit and are located on the upper console floodlight panel. All pilot utility lights are dual (blue-green and white). These lights are portable with coiled cords, attached to each side of the upper console. The lights may be adjusted to direct the light beam or may be removed and carried. The lens of the lights may be turned to change from white to blue-green and/or spot to flood. There is also a utility light, located at the right side of the copilot's seat that can be adjusted for additional illumination of the lower console during night flight.

²⁷⁰ CAAS includes integrated forward-looking infrared (FLIR) and multimode radar for NOE and low-level flight operations in conditions of extremely poor visibility and adverse weather.



UH-60M Blackhawk



CH-47F Chinook



AH-64D Apache

Figure 173. UH-60M Blackhawk (top), CH-47F Chinook (middle), and AH-64D Longbow Apache (bottom).



Figure 174. UH-60M Blackhawk crew station.



UH-60M digital moving map



UH-60M red-orange colored switch guards on center console

Figure 175. UH-60M Blackhawk cockpit displays.

CH-47F Chinook crew station.

The CH-47 Chinook is a tandem rotor, twin engine, heavy transport helicopter. It serves a dual role, carrying either troops or equipment/supplies. The U.S. Army first fielded the CH-47A in 1962. The CH-47 has many variants to include the CH-47D, CH-47F, CH-47G, and the MH-47. The latest model, the CH-47F (fielded in 2007), comes with a fully integrated digital cockpit (Figure 176), the CAAS, and advanced cargo-handling capabilities. The cockpit includes the digital CAAS employing five customizable color AMLCD MFDs capable of presenting flight instrument, targeting, and mapping information (Figure 177, in day and night environments). The CH-47F also incorporates a pair of color AMLCD CDUs that enable the management of the helicopter's radio, navigation, and flight plan information. The cockpit is ANVIS-7 compatible. U.S. Army special operations forces also operate special operations Chinooks, designated as MH-47D and MH-47E, which are being upgraded to the MH-47G configuration.



CH-47F Digital cockpit

Figure 176. CH-47F Chinook digital cockpit. Top row (left to right): MFDs presenting PFD, digital moving, map, Engine Instrument Caution Advisory System (EICAS), and PFD; Bottom row: dual CDUs.



CH-47F CAAS displays

Figure 177. CH-47F Chinook CAAS displays. Top row (left to right): MFDs presenting PFD, digital moving, map, Engine Instrument Caution Advisory System (EICAS), and PFD; Bottom row: dual CDUs.

The overhead switch panel has integrated lighting, adjustable levels of off, dim, and bright. Pilot and copilot instrument panel MFDs also have adjustable integral lighting and can be switched to an ANVIS mode that dim the MFDs to a maximum ANVIS level.

AH-64D Apache crew station.

The AH-64 Apache is a four-blade, twin-engine anti-tank attack helicopter. It has a tandem cockpit, with the pilot located in the rear seat and co-pilot/gunner in the front seat. The AH-64A model was fielded in 1975. The AH-64D Longbow model was fielded in 1997 and features a pair of approximately 6 by 6-inch AMLCD MFDs (referred to as multipurpose displays [MPDs]) in each seat as the primary displays (Figure 178). These occupy the central area of the instrument panel at the pilot's seat (middle) and the left and right edges at the co-pilot/gunner's seat (bottom). Each MFD has independent controls for brightness, contrast, and day-night mode. The day-night mode control varies the operating range of the brightness and color of the display during day or night ambient lighting conditions (Durbin, 2002). The co-pilot/gunner seat also has a Modernized Target Acquisition and Designation System (M-TADS) Electronic Display for presenting FLIR imagery centered between the two MFDs. An Up Front Display (UFD) is located at the top of the dash in both seats. The UFD is a 2.25-inch vertical by 4.5-inch horizontal monochrome (green) LED display. It presents warnings, cautions, and advisories, as well as the status of the communication system (e.g., radio frequencies). A portion of the AH-64Ds feature a rotor-mast-mounted drum to support the "Longbow" system, which consists of millimeter wave fire control radar, radar frequency interferometer, fire-and-forget radar-guided HELLFIRE missile, and cockpit management/digitization enhancements. The difference between the two variants is operationally significant but mechanically minor, since an AH-64D can be field-upgraded to the AH-64D Longbow configuration in a few hours.

Most unique to the Apache models is the monocular IHADSS HMD (Figure 1, p. 2, bottom, right; Figure 179) worn by both the pilot and co-pilot/gunner, which presents FLIR imagery (from either the pilotage or targeting FLIR sensors) with a symbology overlay (Heinecke, 2006). The IHADSS display source is a miniature CRT using a P-43 phosphor, producing green, monochromatic imagery (Figure 166).

Putting color to work in U.S. Army crew station.

As will almost all modern avionics, U.S. Army displays use a variety of colors for the purpose of defining specific indications, functions, or actions. For example, on the EICAS display page in the UH-60M, in what is the typical schema, green is used to indicate normal operating limits for the engines, transmissions, and advisory lights; yellow is used to indicate a cautionary range where the pilot is required to pay particular attention or when a caution light has illuminated indicating a problem the pilot needs to address; and red is used to indicate a safe operating limit has been exceeded, requiring immediate pilot action. The red-green distinction is generally considered to be the most important issue for safe operations and efficient cockpit operations. This does not imply people cannot be trained to recognize the meaning of a warning light or indication by its location or association with an auditory alert. However, reaction time

may be reduced in these cases as the color red tends to elicit an immediate response (R. Ranaudo, personal communication, November 7, 2016).



Pilot rear seat: Fire Detection/Extinguishing Panel (top, left) and Enhanced Up Front Display (communications) (top, right); dual MFDs (bottom, left and right)



Pilot rear seat: full instrument panel



Co-pilot/gunner front seat: FLIR display (center)

Figure 178. AH-64D Apache cockpit displays: pilot rear seat (top and middle) and co-pilot/gunner, front seat (bottom).



Figure 179. AH-64 Apache IHADSS HMD, which displays FLIR imagery with symbology.

In addition to the green-yellow-red scheme, commonly used colors on MFDs are cyan (greenish-blue), magenta (purplish-red), and white. One special color combination is the use of cyan (sky) and brown (ground) to present an attitude indicator (artificial horizon) flight page (Figure 180) (Department of the Army, 2015c). The dominant background color for the MFDs is black, a selection to enhance color contrast (Figure 181). However, text labels and messages can be presented as black text with red, yellow, or white backgrounds (e.g., on the Ch-47F fuel screen [Figure 182] [Department of the Army, 2013]).

The AH-64D MFDs use seven colors (Department of the Army, 2015c):

- Green for normal (default), advisory conditions
- Red for warnings, enemy threats
- Yellow for cautions, hazards
- White for attention
- Cyan for friendlies, sky of attitude indicator
- Brown for ground of attitude indicator
- Black for background

In addition, partial intensities of any of these colors can be used to de-emphasize normal conditions (e.g., partial green may appear blue-green; partial yellow may appear brown or orange).

In addition to the colors presented on the MFDs, color has presence in all aircraft in the form of identification/location aids for safety features. Red is used for covers for some switches. Fire handles are illuminated red to bring quick attention to the pilot when needed, yellow (in an alternating yellow-black band configuration) is used to outline levers or switches that can jettison components off the helicopter such as doors, windows, external tanks, rockets, missiles and sling loads. Adjustable electro-luminescent markings are used on instrument panels for switch identification during day, night and ANVIS conditions. Some of these examples are summarized

in Table 17 and presented in Figures 183-186 for the UH-60M, CH-47F, and AH-64D. Supplemental safety equipment, e.g., hand fire extinguishers and first aid kits, are color-coded for easy location during emergencies (e.g., Figure 183-184).

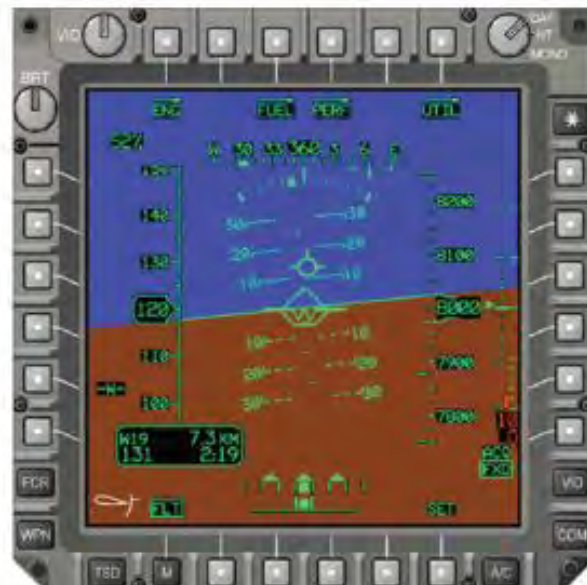


Figure 180. Use of blue and brown to present an attitude indicator on an MFD in AH-64D Apache (Department of the Army, 2015c).



Figure 181. Use of black as background color to enhance color contrast on engine page of MFD in AH-64D Apache (Department of the Army, 2015c).

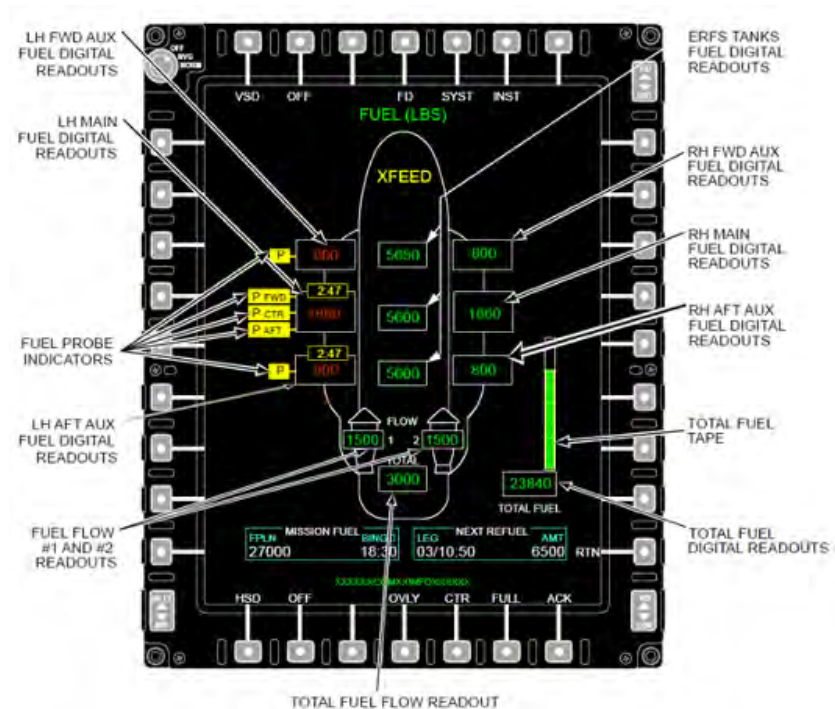


Figure 182. Use of black text on yellow background on fuel page displayed on MFD in CH-47F Chinook (Department of the Army, 2013).

Table 17. Examples of cockpit color use other than on MFDs.

Aircraft	Feature	Color(s)
UH-60M Blackhawk	Stabilator test button	Red
	Hand-operated fire extinguisher (Figure 183, left)	Red
	Emergency exit release handle	Yellow-black banding
	Cargo hook emergency release button (Figure 183, right)	Red button with yellow-black banding
CH-47F Chinook	Troop warn panel switch indicators on overhead switch panel (Figure 184, top, right)	Red, yellow-white-black banding
	Cabin and ramp lights	Blue, white
	Fire pull handles (Figure 184, bottom)	Yellow-white banding
	Cargo compartment fire extinguisher (Figure 184, top, left)	Red
AH-64D Longbow Apache	Exterior canopy jettison handle (Figure 185)	Orange-yellow-black diagonal striping
	Fire detection/extinguishing system switch guards	Orange-yellow-black diagonal striping
	EMERG HYD (emergency hydraulic pressure) button on Emergency panel (Figure 186)	Yellow-white banding



Fire extinguisher



Cargo hook emergency release button

Figure 183. Examples of additional color usage in UH-60M: hand-held fire extinguisher behind pilot's seat (left); and emergency cargo hook emergency release button (right).



Cargo compartment fire extinguisher



Troop warn panel



Fire pull handles

Figure 184. Examples of additional color usage in CH-47F: cargo compartment fire extinguisher (top, left); troop warn panel indicators (top, right); fire pull handles (bottom).



Figure 185. Exterior side canopy jettison handle on AH-64D.



Figure 186. Yellow-white banding around EMERG HYD button on the Emergency Panel in AH-64D that provides hydraulic power.

Special Color Issues in U.S. Army Aviation

There are a number of special color-related issues impacting pilot performance in Army crew stations. Two of these issues are driven by the Army's need to operate at night or during periods of low illumination: crew station lighting and the use of night vision devices presenting monochromatic imagery. A third issue relates to the visual impact of viewing color displays through sunglasses, tinted visors, and other ancillary optical devices. While none of these issues are unique to Army aviation, they are arguably of greater concern to Army pilots because of the types of flight profiles flown; the most demanding of these is referred to as NOE flight. NOE is defined technically as a flight profile of varying airspeed and altitude usually performed below 25 feet AGL and below 40 knots airspeed (Department of the Army, 2005). In practice, during NOE flight, pilots vary airspeed and altitude so as to maintain the aircraft as close to the earth's surface as vegetation, obstacles, and ambient light will permit.

A fourth issue is the enviable development and fielding of color HMDs. Current U.S. Army HMDs present all symbology monochromatically. However, recent advances in display technology allow for showing color symbology, to include green, red, yellow, and various combinations of these colors (Havig, Grigsby, Heft, LaCreta, & Post, 2001). Color is one of the latest design characteristics of HMDs. It's inclusion in design specifications is based on two suppositions: 1) color provides an additional method of encoding information, and 2) color provides a more realistic, and hence more intuitive, presentation of information, especially pilotage imagery. To some degree, these two perceived advantages have been validated with head-down panel-mounted displays, although not without a few problems associated with visual physiology and perception (Harding, Rash, Lattimore, Statz, & Martin, 2016). One problem is

associated with color mixing, confounded by the lighting environment. For example, symbology colors on a see-through HMD will sum with the colors from outside the cockpit. Further, the bright lighting of day flight operations would cause the colors displayed to desaturate or become closer to the predominant ambient or background hue. If this happens, pilots could have trouble differentiating (for example) between a green and a yellow. Sufficient luminance contrast is required for symbology to be distinguishable from one another. These problems will likely become more prevalent when the user population expands beyond military aviators to a general user population, of which a significant portion may have color vision deficiencies (Harding et al, 2017).

Crew station lighting.

One special issue is the association of color with the need to illuminate displays and provide general illumination in the cockpit during night flight, but without compromising pilots' innate night vision (during the early years of aviation) and their night vision use of I² devices (in the modern cockpit), which is driven by the ANVIS-compatible lighting issue.

While mostly of historical interest today, a discussion of this issue begins with a debate that raged for decades over which color lighting (red vs. white) was best during night flying for maintaining pilot dark adaptation (a serious issue in early military aviation) and the ability to read navigation maps. This debate played an important role in the evolution of cockpit lighting.

During the period from WWII to the current dominance of MFDs in the modern cockpit, the aviation lighting community debated the merits of red vs. white as the predominate lighting in the cockpit (Hartley & Young, 1941). The major concern was the presumed need to preserve night vision capability through the pilot's maintenance of dark adaptation (Hartline, McDonald, & Millikan, 1941; Hecht & Hsia, 1945). Prior to WWII, two systems of artificial lighting were in common use in military aircraft. UV lighting was used by the U.S. Air Forces (precursor to USAF) from 1940 to 1947 and by the German Luftwaffe throughout the war (Taylor, 1985). Red cockpit lighting was used by the RAF and the U.S Navy from the 1930s and was adopted by the USAF in the 1950s.

Haldran Hartline,²⁷¹ an American physician and physiologist, found during his work with film development he adapted well to darkness under red lighting conditions. Working for the USN, Hartline demonstrated red-lighted instruments were readable at low-light levels. Some of his other work with the human retina had shown the rods are almost totally insensitive to red. As a consequence of his recommendations, the U.S. Army and USN began using red light in their cockpits in the 1940s (Hartline, 1944; G. W. Godfrey, personal communication, July 10, 2003).

To produce red lighting during an era when incandescent lamps were the primary light source, the light from the lamps was filtered. This increased the cost of the lighting, generated heat in the instrument panel and prompted manufacturers to question whether there was really an advantage to using red lighting in place of white lighting.

²⁷¹ Haldan K. Hartline was an American physiologist who was a co-recipient of the 1967 Nobel Prize in Physiology or Medicine for his work in analyzing the neurophysiological mechanisms of vision.

Hartline's conclusions were supported by numerous other studies on dark adaptation. In 1982, faced with the question of the compatibility of night vision devices (e.g., ANVIS) and cockpit lighting, the U.S. Army reviewed the issue. An Army report that compared the effects of red lighting and blue-white lighting (which uses a blue filter to compensate for an incandescent lamp's tendency to turn yellow as it is dimmed) on dark adaptation under operational conditions said, "Under conditions of total or nearly total darkness, red lighting preserves visual sensitivity for outside viewing to a greater extent than does blue-white lighting. This is true even when instrument lights are set at the low levels...at which (U.S. Army) aviators normally set their instruments (Holly and Rogers, 1982)." Nevertheless, the report also said that with a full moon illuminating a clear sky, the difference between the two lighting schemes "vanishes."

Other studies have examined the advantages of white light. In his book, *Human Factors in Flight*, Frank Hawkins (1987) cited a number of advantages, including that white light reduces eye fatigue, improves instrument and display contrast, provides better illumination in thunderstorms and daylight, and permits effective color coding. With red light, the color coding on some aeronautical charts and some flight instruments disappears – the information is readable, but color differentiation among symbols cannot be seen (Jacobsen, 2003).

Mittelman (2000) states red lighting on the flight deck requires more focusing power than white light or blue-green light for near objects to be observed clearly. This may cause difficulty especially for pilots in their 40s and older with presbyopia – the most common age-related change in vision – in which the eyes become less able to focus on nearby objects. This is one reason why some modern transport aircraft crew station designs attempt to reduce or eliminate the overhead panel. For pilots who wear glasses, having to look up at the overhead panel, especially at night is hard to do and is both visually and physically fatiguing.

Nevertheless, following a 1949 USN and USAF subjective evaluation of cockpit lighting (Hitchcock, 1975), red lighting became the standard for military aircraft and some nonmilitary aircraft and functioned well until the introduction of night vision devices (e.g., INVIS and ANVIS), multicolored CRT displays, and active-matrix LCD displays, which were found to be incompatible with red lighting. Studies determined ambient red lighting does not provide true dark adaptation but instead provides color adaptation. The rods and cones adapt to the red wavelengths; consequently, the pilot may have difficulty discriminating between some colors on the color display. Partly to address this issue, the USAF decided to use blue-white lighting on its flight decks (Tredici, 2003).

Most commercial aircraft use unfiltered white lighting to reduce costs. Blue-white lighting on an instrument panel requires about 30% more lamps than white lighting. That requires a bigger power supply, which in turn requires more weight, which decreases useful load (Khashoggi, 2003). Until the advent of MFDs in the 1980s, most commercial airliners used unfiltered white lighting.

Today's airliners generally utilize unfiltered white light at crew stations for both panels and instruments (except flat-panel displays). For example, according to Alan R. Jacobsen, Boeing Commercial Airplanes, all current Boeing airplanes use unfiltered white light. Pilots are able to dim area lighting and instrument lighting to "appropriately low levels to allow sufficient

dark adaptation for nighttime operation” (Jacobsen, 2003). Those appropriate levels were determined by HF evaluations. The aircraft also are equipped with storm lighting “in which the flight deck lighting can be driven to fairly bright levels with the flip of a switch” to counter the loss of dark adaptation resulting from lightning flashes.

John K. Lauber, Vice President for Safety and Technical Affairs at Airbus, has stated the Airbus also uses unfiltered white light on the flight decks of its airplanes. Lauber states “using red light to protect night vision may have been important at one time but is probably not so significant now, with modern lighting systems, both airborne and ground-based” (Rash & Manning, 2003).

Modern corporate/business aircraft have white EL panels and incandescent instrument lighting (except when flat-panel displays are used). Most smaller general aviation aircraft are equipped with incandescent post lighting for instruments and post-lighted indicia (plates) for legends and circuit breaker panels.

The USAF currently uses blue-white incandescent lighting for both panel and instrument displays (except flat-panel displays) at crew stations not requiring utilization of a night vision imaging system (NVIS). A blue filter sometimes is placed over incandescent lamps to compensate for a yellowing that occurs when they are dimmed. The USN and U.S. Army use red incandescent lighting for both panels and instruments (except when flat-panel displays are used) in aircraft where an NVIS is not used (which is rare today for the U.S. Army). In aircraft in which an NVIS (e.g., ANVIS for the U.S. Army) is used, blue-green NVIS-compatible lighting is employed. The blue-green lighting is required because an NVIS has a spectral sensitivity favoring the red end of the EM spectrum, including both the red region of the human visible spectrum and the invisible IR region. This characteristic is enhanced by a blue cutoff filter preventing virtually all blue light from being seen. This blue filtering is based on the ANVIS filter classes discussed earlier, which give rise to four ANVIS (INVIS) cockpit lighting designations defined in Department of Defense (2001) standard for lighting, aircraft, Night Vision Imaging System (NVIS) compatible (MIL-STD-3009):

- NVIS Green A – The color for primary, secondary, and advisory lighting. The chromaticity limits are within a circle of radius 0.037 with the center at $u' = 0.131$, $v' = 0.623$.
- NVIS Green B – The color for special lighting components needing saturated color (monochromatic) for contrast. The chromaticity limits are within a circle of radius 0.057 with the center at $u' = 0.131$, $v' = 0.623$.
- NVIS Yellow – The color for master caution and warning signals in Class A cockpits. The chromaticity limits are within a circle of radius 0.083 with the center at $u' = 0.274$, $v' = 0.622$.
- NVIS Red – The color for warning signals in Class B cockpits. The chromaticity limits are within a circle of radius 0.060 with the center at $u' = 0.450$, $v' = 0.550$.

Monochromatic imagery.

Since the U.S. Army adopted night operations as a mainstay of its operational doctrine, two night vision imaging systems, ANVIS and the AH-64 Apache IHADSS, dominate U.S. Army cockpits. Both of these devices provide monochromatic P-43 imagery to the pilot.

These monochromatic displays have produced some problems, with chromatic aftereffects reported with both devices. This problem first was raised in the early 1970s (Glick and Moser, 1974). This afterimage phenomenon was reported by U.S. Army pilots using GEN II NVGs for night flights. It was initially, and incorrectly, called brown eye syndrome. The reported visual problem was that pilots experienced only brown and white color vision for a few minutes following NVG flight. Glick and Moser (1974) investigated this report and concluded the aviator's eyes were adapting to the monochromatic green output of the NVGs. When such adaptation occurs, two phenomena may be experienced. The first is a positive afterimage seen when looking at a dark background; this afterimage will be the same color as the adapting color. The second is a negative afterimage seen when a lighter background is viewed. In this case, the afterimage will take on the complement color, which is brown for the NVG green. The final conclusion was this phenomenon was a normal physiological response and was not a concern. A later investigation (Moffitt, Rogers, and Cicinelli, 1988) looked at the possible confounding which might occur when pilots must view color cockpit displays intermittently during prolonged NVG use. Their findings did suggest possible degraded identification of green and white colors on such displays, requiring increased luminance levels.

A similar visual aftereffect phenomenon has been reported by AH-64 Apache pilots. Behar et al. (1990) conducted a three-part study assessing the visual performance of 50 AH-64 Apache instructor pilots at Fort Rucker, AL. The first part, accomplished by written questionnaire, was primarily an epidemiological appraisal documenting visual problems experienced by the Fort Rucker Apache instructor pilot population. Approximately 20% of all subject pilots reported the presence of afterimages following Apache flight. In comments obtained in the study, several pilots indicated that following long (>2.5 hours) flights using FLIR imagery presented on the IHADSS, color afterimages would persist for 2-3 hours.

Color realism.

The explosion of color display and multi-spectrum sensor technologies has provided impetus for the development of full-color flight imagery to replace monochromatic flight imagery. False and pseudo-color imagery has been surpassed by the drive for *color realism*,²⁷² where colors used in a display presentation match expectations or mental models of color in a scene or for specific information. A common, but simplistic, aviation example of employing pictorial color realism is the use of blue and brown for the sky/ground background of attitude indicators (Figure 187).

The concept of color realism as applied to pilotage and targeting imagery, will most likely be through the inclusion of imagery from standard video cameras, low-light level CCD sensors, IR and I² night imaging systems (mounted on the aircraft or pilot), as well as fused

²⁷² The term *color realism* also is used to refer to the theory that color is a real property of an object (Byrne & Hilbert, 2003).

multispectral,²⁷³ enhanced, and synthetic (computer-generated) imagery. Both real and synthetic color can be present in these individual, and combinations of, sensory imaging sources.



Horizon indicator

Figure 187. Attitude indicator, demonstrating the principle of pictorial realism.

A generalized assumption is that providing realistic full-color images of the outside world is intuitively a correct approach. Such is the case for programs that have pursued real-time image fusion for night pilotage (Aguilar et al., 1998; Ryan & Tinkler, 1995; Steele & Perconti, 1997) and the development of a color ANVIS as an upgrade to the currently fielded, monochromatic, P-43 phosphor ANVIS (see *I*² section).

There are a large number of complex and interacting factors involved in determining the effectiveness of both color realistic displays and the imagery they are capable of presenting. However, it is possible full-color display presentations may introduce a new subset of problems for the pilot. While many of such problems may be associated with display concepts in general, many others may be related specifically to the production and use of color. Hopkin (1992) has pointed out the importance of considering the aesthetics of color usage. Too much color may inadvertently draw user attention towards the coding and away from vital information in displays, which would be using color symbology overlaid unto color imagery. He cautions “too much saturation, too many colors, excessive contrast or brightness, non-adjustable saturation or brightness, uncoordinated colors, colors that don’t blend with other displays, and colors not needed, (can) all lead to potential color display problems.”

Addressing this question following the introduction of full-color AMLVDs was the task assigned to the Workshop on Application Principles for Multicolored Displays (Kinney & Huey, 1990), which was convened in 1985 by the Committee of Human Factors. The committee consisted of 15 subject matter experts from the disciplines psychology, engineering, biomechanics, physiology, medicine, cognitive sciences, machine intelligence, computer sciences, sociology, education, and HFE. These members were subject matter experts in the areas of display systems engineering, color perception and color, HFE, industrial design, graphics engineering, and systems engineering application.

²⁷³ Multispectral fused imagery can include many wavelength bands, ranging from the visible through short- and long-wave IR (SWIR/LWIR), as well as synthetic aperture radar (SAR) imagery. Image fusion attempts to extract and combine the characteristic image features of each source type. The primary goal of fused imagery is to improve situation awareness.

The committee began their task with a basic set of assumptions:

- Human prefer color – this has been borne out by the commercial success of color in televisions, motion pictures, photography, and advertising print.
- Relative to monochromatic displays, multicolor displays are more complex, making them more expensive to design, build, and maintain – although newer technologies can reduce costs over time.
- The addition of color to a display can sacrifice both display and user performance – for example, display resolution may be reduced; and human error rates can result if color is applied improperly.
- Color vision, while almost universally experienced, is poorly understood by display designer – this is frequently coupled with a lack of understanding of the complexity of color science.

While a great area of interest in the field of military aviation, color realism is frequently an overlooked aspect by consumers in the performance of entertainment televisions. However, it has been one of the goals of recent advances by television display manufacturers (Morrison, 2015a). It is an ongoing effort to reproduce richer, more lifelike colors. To achieve this goal, manufacturers must combine greater color (or bit) depth with a larger color gamut (see *Color spaces and models* and *Digital color* sections). Current high definition televisions (HDTVs) use an 8-bit depth for a possible 256 shades for each color. Industry is moving towards a 10-bit depth, 1,024 shades per color. Increased color gamuts resulting from the adoption of new color standards, coupled with a greater bit depth will have dramatic effects on color realism. Newer technologies such as quantum dots can be expected to improve color realism even more (see *The future of color* section).

Ancillary optical devices.

In early aviation history, all military pilots flew, day or night, with the naked eye. Today, with the U.S. Army's emphasis on night operations, pilots are frequently seeing the external world through ANVIS or see-through HMDs. Even in the less-frequent circumstances of unaided flight, pilots often view the real world through sunglasses and/or visors. In most military aviation operational environments, aircrew employ a host of ancillary optical devices, often multiple devices, simultaneously: sunglasses, prescription eyewear (e.g., lenses and contacts), visors (e.g., clear, tinted, laser protective), and nuclear, biological, and chemical (NBC) masks (Figure 188). Any of these, singularly or in combination, can have a significant influence on color perception depending on the device's filtering characteristics. In certain cases, specific colors may become invisible, as they are completely removed by the filtering (Menu et al., 2001).

No colored filter can be placed in front of the human eye without degrading some aspect of the color scene being viewed. The filter will reduce overall light transmission, alter color contrast, or block selective wavelengths, impacting color perception of electronic displays, maps, and the outside world.

Sunglasses.

However, standard aviator sunglasses and visors are neutral density optical devices, theoretically spectrally neutral in transmission over the visible spectrum. Aviator sunglasses (historically identified officially as Helmet Gear Unit 4P [HGU-4P] since 1958) are specified in MIL-S-25948, Sunglasses, HGU-4P (Department of Defense, 1984). They are required to provide eye protection against sunlight glare and UV components of sunlight and allow 15% transmission of visible light. However, most pilots obtain their sunglasses from commercial sources. This has led to some vision issues.

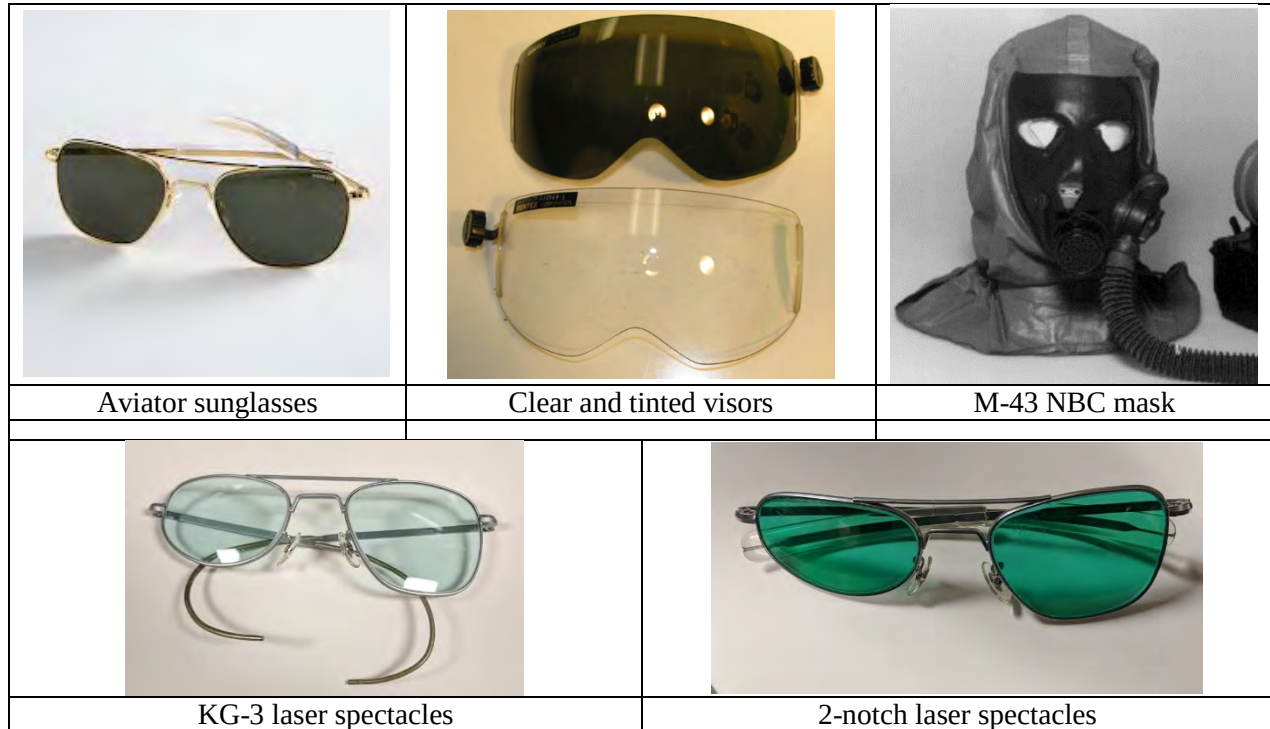


Figure 188. Examples of ancillary optical devices: Aviator sunglasses (top, left), clear and tinted visors (top, middle), M-43 NBC mask (top, right), KG-3 laser spectacles (bottom, left), and 2-notch laser spectacles.

In the mid-1990s, pilots were reporting difficulty in discriminating colors of warning lights while wearing sunglasses made from CR-39 plastic lenses. An investigation of a sample of Army aviator worn sunglasses at that time found considerable variation in both spectral and overall luminous transmittance (Rabin, Wiley, Levine, Wicks, & Rivers, 1996). It was determined that variability in commercial transmittance meters was a contributing factor to acceptance of sunglasses not meeting specifications.

Another problem also can be encountered with sunglasses. Pilots often select sunglasses offering glare attenuation, usually with polarized lenses (Rash & Manning, 2002). Glare should not be confused with ambient brightness – the overall intensity of sunlight. Glare is produced by light sources and reflections that are of much higher intensity than ambient light intensity. In the aviation environment, a typical example of glare is the reflection of light off a surface, such as

metal, water or clouds. A pilot flying an aircraft at 40,000 ft often encounters significant glare from the cloud layer below.

Because glare is associated with extremely high light intensity, using tint alone for glare reduction would result in lenses that are too dark and unacceptable for visual acuity. A more effective glare-reduction technique involves polarized filters. Light waves from the sun and from artificial light sources, such as light bulbs, vibrate and radiate outward in all directions. If the light – by transmission, reflection or scattering – is affected so its vibrations are aligned into one plane of direction or more, the light is said to be polarized. Polarization can occur naturally or artificially.

Glare most frequently encountered in the aviation environment comes from horizontal surfaces such as water. When light strikes the horizontal surface, the reflected light waves are polarized to the angle of that surface. A highly reflective horizontal surface, such as a lake, produces mostly horizontally polarized light. The polarized lenses in sunglasses are polarized at a fixed angle allowing only vertically polarized light to be transmitted, thereby eliminating a significant amount of glare. In addition, their blocking of polarized light can cause problems in performing some tasks. Some aircraft have flight instruments that incorporate polarizing anti-glare filters. When these instruments are viewed through polarized sunglasses, the information on the displays can disappear. Newer electronic instruments with liquid crystal displays also can become unreadable at some angles when viewed through polarized sunglasses.

While neutral density gray lenses are recommended, sunglass lenses are available in many colors. The lens color primarily is determined by which parts of the visible light spectrum are absorbed or reflected by the lenses. The oldest method of coloring sunglass lenses involves a process called constant density, in which the color is built into the lens material to produce uniform color throughout each lens. Colored polycarbonate lenses can be produced by applying a coat of light-absorbing molecules to the surface of clear polycarbonate lenses. Another method of coloring polycarbonate lenses is to immerse them in a liquid containing the coloring dye; the dye is absorbed slowly into the lens. A darker color is achieved by leaving the lenses in the liquid for a longer period of time. Some sunglass lenses are gradient lenses, which are darker in the upper area than in the lower area. The upper area provides protection from sunlight and glare, and the lower area provides enough light transmission for the pilot to see instruments and to read charts.

Preferred gray lenses reduce the overall brightness with the least color distortion. Green lenses also reduce brightness with minimal color distortion. Lenses of most other colors cause color distortions to varying degrees. Brown lenses – sometimes recommended for improving contrast in hazy sunlight – also may distort colors. Yellow lenses filter out most of the incoming blue light and allow a larger proportion of other colors to be transmitted. The yellow color virtually eliminates the blue part of the spectrum, and many users report these “blue-locking” lenses make everything appear brighter and sharper. However, a 2000 review of more than 200 studies conducted since 1912 to investigate visual performance with yellow lenses found none of the studies had identified any measurable improvement in visual acuity, contrast sensitivity or detection capability (McLean, Rash, & Schmeisser, 2000).

In addition, the review found negative aspects of wearing yellow lenses, including distortion of color perception. When the blue portion of the color spectrum is removed from a scene, there are certain predictable effects on color shifts within that scene: Blue is attenuated or removed, and white is perceived as yellow. Advocates of blue-blocking lenses say that these lenses sharpen images in the presence of haze. The appearance of haze is basically white, which means its spectral content is a balance of red, green and blue components. When the blue component is filtered out, the haze is not as apparent to the observer, but visibility through the haze remains essentially the same.

Visors.

In U.S. Army aviation, visors are classified as Class I or II. These classes are defined in detail specification MIL-DTL-43511D, Visors, flyer's helmet, polycarbonate (1990). Class I visors are clear, having a photopic (daytime) luminous transmittance of 85% or greater. Class II visors are neutrally tinted, having a photopic luminous transmittance between 12-18%. An exception to the Class II luminous transmittance requirement is granted to the tinted visor used in the Integrated Helmet Unit (IHU) of the IHADSS in the AH-64 Apache. The IHADSS Class II visor has a photopic luminous transmittance between 8-12%. This lower range of transmittance is needed to improve visibility of real-time imagery provided on the IHADSS HMD.

Laser protective visors are an addition visor type. These visors, by design, selectively attenuate specific wavelengths or wavelength bands. While security issues prevent describing actual visual perception changes due to specific laser wavelengths, there are a few studies that have modeled the type of changes that might be expected. Williamson & Boontanrart (2015) demonstrated via modeling the potential of laser protective visors to produce difficulties in viewing color displays either through “misinterpretation of color cues or masking specific colors completely.”

When the U.S. Army's AH-64 Apache helicopter was be operationally tested prior to its initial fielding, a requirement to provide protection against its own laser rangefinder drove the development of a modified spectacle to be used under the IHADSS' unique HMD optics (Figure 188, bottom, left). Laser protection was achieved using KG-3 glass, a material that absorbs energy at wavelengths between 0.9 and 12 μm . KG-3 glass is considered transparent in the visible spectrum but does present with a green cast (Chiou, 1977). The Apache's rangefinder is a Nd: YAG laser operating at 1.06 μm . KG-5, with a slightly higher attenuation at 1.06 μm , later replaced KG-3, and in the late 1980s, a 2-notch (Ruby and Nd: YAG) CR-39 lenses were used (Figure 188, bottom, right).

Color HMDs.

In U.S. Army aviation, the two longest-fielded HMDs presenting night sensor imagery are monochromatic systems: the ANVIS/NVG and the IHADSS. Both present imagery as green on black. Without consideration to any engineering or HF issues with development and implementation, color is an expected feature of future HMDs by the user community. This expectation arises from color being a very conspicuous, natural, and important attribute of real-world objects and scenes (Kinney & Huey, 1990). Color can provide three functions: serve as the

actual work object, support cognitive functions, and assist in spatial orientation (Spenkelink & Besuijen, 1996). Although color may not be the solution for every task (Andre & Wickens, 1995), overall, adding full color to HMDs has the potential to reduce workload and improve visual performance (Melzer & Moffitt, 1992).

Full-color HMDs have been late in development due mostly to their higher cost, complexity, and weight, e.g., the use of color image sources increases the complexity of the relay optics design, since a polychromatic design must be used. In general, color displays require resolution and luminance tradeoffs. However, these factors have not decreased their desirability to the user.

Although not clear as to its full potential to reduce the complexity of color HMD design, one aspect of the human retina offers an interesting approach. Because of the non-uniform distribution of the three types of cones in the retina, color imagery may not have to be supported across the full field-of-view of the HMD (Keller & Colucci, 1998) (see *Anatomy and Physiology of Color Vision* and *Color Vision* sections).

Efforts to develop color HMDs date back at least to the 1970s (Winner, 1972; Post et al., 1994) when Hughes Aircraft under the direction of the U.S. Air Force Armstrong Laboratory, Wright-Patterson Air Force Base (WPAFB), Ohio, produced a monocular display around a miniature, 1-inch, P-45(white) CRT that used a rotating filter to provide field-sequential color (FSC).²⁷⁴ Since this effort, a number of other attempts based on multiple image source technologies and methods have been made. Until the advent of flat-panel display technologies, the most pursued approach to providing full color in an HMD had been FSC. Today, LCDs have become the most dominant display technology.

FSC displays are attractive for HMD applications because they have a resolution advantage over conventional color displays. However, they are prone to the image-quality problem of color breakup when run at the usual 180-Hz field rate. Post, Monnier, & Calhoun (1997) looked at this problem and developed a model for predicting whether this breakup will be visible for a given set of viewing conditions. For the ranges of viewing conditions tested (i.e., luminance and contrast), their model yielded similar predictions as previous work (Arend, Lubin, Gille, & Larimer, 1994).

The 1990s saw a number of research and simulator color HMDs associated with programs (): a) CONDOR – Covert Night/Day Operations in Rotorcraft (joint US/UK) (Kanahele & Buckanin, 1996); b) RASCAL – The Rotorcraft Aircrew/Systems Concept Airborne Laboratory (joint NASA/U.S. Army) (Hindson, Njaka, Aiken, & Barnhart, 1994); SPIRIT – Simulation Program for Improved Rotorcraft Integration Technology (joint US/Canada) (Jennings, Swail, Craig, & Lasnier, 1999)

Full-color capability is now widely available via all of the flat panel display technologies, including LC, EL, LED, field emission, and plasma. AMLCDs are currently the desired color display choice for cockpit displays (Livada, 2012; Desjardins, 2013) with active-matrix OLEDs

²⁷⁴ A *field-sequential* color system is a color display system in which the primary color information is transmitted in successive images, relying on the human vision system to fuse the successive images into a color picture.

(AMOLEDs) rapidly becoming a competing technology (Fellowes, Wood, Prache, & Jones, 2005; Savastano, 2012).

The highest luminance image source available is the laser. Making use of the persistence of vision characteristic of the eye, lasers are used in a scanning mode to produce an image in the manner of CRTs. Rather than an electron beam, a laser beam is scanned in two dimensions, with the beam intensity modulated at every pixel (Rash, 2000). When scanned at frequencies greater than 60 Hz, a flicker-free image is produced. In addition to high luminance, laser-based displays are capable of a wide color gamut with excellent color saturation.

One of the original versions of these displays is known as a virtual retinal display (VRD). The VRD modulates the scanning laser beam with video information, producing a raster image placed directly onto the retina of the user's eye (Johnston & Willey, 1995). The VRD may also include a depth accommodation cue to vary the focus of scanned photons rapidly so as to control the depth perceived by a user for each individual picture element of the virtual image. Further, an eye tracking system may be utilized to sense the position of an entrance pupil of the user's eye, with the detected pupil position being used to move the beam so as to be approximately coincident with the entrance pupil of the eye (Furness & Kollin, 1995).

Also known as the Retinal Scanning Display (RSD), the VRD concept originated at the Human Interface Technology Laboratory at the University of Washington (Furness and Kollin, 1995) and was developed at Microvision, Inc., Redmond, Washington, for the U.S. Army's Virtual Cockpit Optimization Program (VCOP) as a virtual cockpit simulator (Figure 189) (Bayer, Rash, & Brindle, 2010). This system offers high spatial and color resolution and high luminance, fundamentally limited only by eye safety considerations. It does not require the use of a display screen. Color imagery is achieved by the use of low-power red, green, and blue lasers.

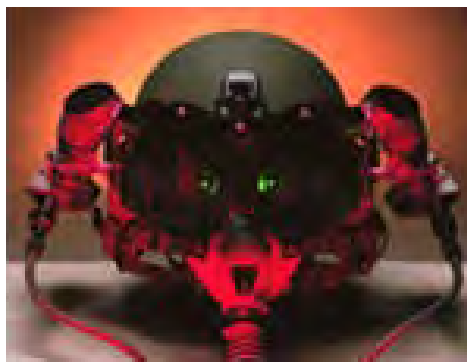


Figure 189. Microvision, Inc., Retinal Scanning Display (RSD).

Due to optical constraints imposed by inherent design characteristics, the final image in HMDs using laser sources is not scanned directly onto the viewer's retina. Instead, an intermediate image must be formed and viewed using an eyepiece. This configuration is no longer a true VRD and is better described as a scanning laser display.

While laser-based displays offer the advantages of high luminance and wide color gamut, they typically suffer from coherence artifacts. Fortunately, the RSD generates pixels serially, which makes the pixels mutually incoherent; any remaining coherence (e.g., speckle) is typically at subpixel level, hence at high spatial resolution that is beyond the human eye's discerning capability.

While not all are targeted for U.S. Army applications, a number of color source HMD systems for training, simulation, and fielding have been, or are currently being, developed by BAE Systems, Inc. (e.g., Q-Sight®) (Figure 190, left), Elbit Systems of America (e.g., Helmet Display and Tracker System [HDTs]), L-3 Link Simulation and Training (e.g., Advanced helmet Mounted Display [AHMD]), Microvision (e.g., Spectrum® SD2500), Rockwell Collins, Inc. (e.g., SimEye SR100A), Thales Visionix, Inc. (e.g., Scorpion® Helmet Mounted Cueing System [HMCS]), and other avionics manufacturers (Bayer, Rash, & Brindle, 2010).

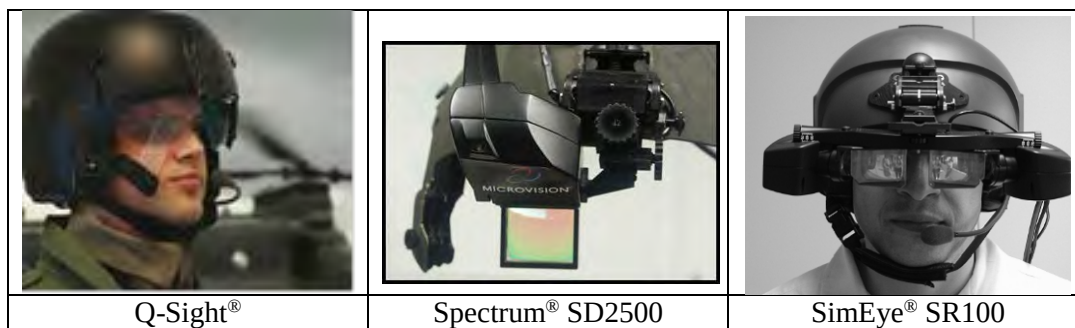


Figure 190. Examples of color HMDs: BAE Systems Q-Sight® (left); Microvision, Inc., Spectrum® SD2500 (middle); and Rockwell Collins, Inc., SimEye® SR100 (right).

Looking in detail at one of these examples, in 2008, Rockwell Collins, Inc., built the SR100, a full-color HMD for the U.S. Army's Aviation Combined Arms Tactical Trainer (AVCATT) reconfigurable manned module simulator using a high-resolution SXGA²⁷⁵ (1280 x 1024) color Ferroelectric Liquid Crystal on Silicon (FLCOS) image sources (Melzer & Porter, 2008). The fast bi-stable ferroelectric liquid crystal properties are leveraged to create a high quality color image using Time Domain Imaging™ technology. Each pixel in the FLCOS display device is either white or black. To produce colors, the individual primary color image element (i.e., red, green, or blue) is displayed while simultaneously being illuminated by the appropriate primary color. All three color sub-frames are presented within a small frame time. To produce gray shades, the pixel is temporally modulated and dithered, with relative brightness determined by the duty cycle in the "on" state. Sophisticated electronics synchronize the display operation with the illumination. The persistence of vision of the human eye acts as a low-pass temporal filter to produce a smooth full-color image. It is noted any color sequential or dithered display can be susceptible to temporal image artifacts such as flicker, color-break up or false contouring if not implemented properly.

²⁷⁵ *Super Extended Graphics Array*, a display specification that is capable of displaying a resolution of 1280 x 1024, or approximately 1.3 million pixels.

While cost factors and complexity issues for color HMD design have disappeared with mass-production of miniature LCDs, the implementation of color in HMDs does have some issues. The luminous efficiency of the eye is a function of wavelength and adaptation state. In the photopic state, the eye is most efficient at 555 nm, requiring greater energy at other wavelengths to achieve equal luminances.

Even for existing optical see-through HMDs, it is a common challenge for the displayed image to provide sufficient luminance and contrast when viewed against the real-world scene. Fares & Jordan (2015) have stated that in eyes-out display devices, even with a wide color gamut, the effectiveness of color symbology remains debatable. They caution that “designing a robust set of color symbology, for all eyes-out display types and in all conditions of operation, could be less straightforward than in HDDs.” In fact, the transparency dimension of the display can cause a departure between the intent of the color symbology and its recognition/discrimination by the user. This is a result of the result of see-through HMDs being a color additive process. The hue achieved by a mixture of symbology and ambient scene can be any color on the line between the two colors depending on their relative luminances. This design problem may be reduced if a clear relationship is established between color gamut and cockpit task workload (see Issue #5 in *New and Continuing Color Issues and Future Research* section). However, another solution is having an adequate luminance requirement for color symbology. The importance of this requirement (as well as one for color contrast) has been raised before by Havig, Grigsby, Heft, LaCreta, & Post (2001) and Martinsen, Havig, Heft, LaCreta, & Post (2002), and more recently by Harding et al. (2017) (see Issue #6 in *New and Continuing Color Issues and Future Research* section).

Color as a Factor in U.S. Army Aviation Accidents

The military aviation environment is complex and inherently unforgiving (Taneja, 2002; Wiegmann & Shappell, 2003). Even the smallest unexpected or unintentional action or reaction can cascade into a chain of events²⁷⁶ ending in an accident (Hiner, 2002). In addition to human and material costs, accidents can have a significant impact on aircraft design and operational practice in aviation (King, 2011).

A few studies have shown pilots with CVDs commit more errors and are slower in recognizing aviation signals and color-coded instrument displays (Cole & Maddocks, 1995; Squire, Rodriguez-Carmona, Evans, & Barbur, 2005; Vingrys & Cole, 1986). Even with normal color vision, hazards attributed to the use of color can still exist (Defence Science and Technology Agency, 1981).

The U.S. Army identifies three major causes of accidents: human, materiel, and environmental factors. Human causal factors relate to human errors, which are mainly those inherent to human design, function and behavior. Materiel factors include equipment failure and damage that can result from design flaws or system (or component) failure. Environmental factors include noise, illumination, and weather conditions (e.g., precipitation, temperature, humidity, pressure, wind, and lightning), which can adversely affect the performance of the individual or equipment (Department of the Army, 1994). Causal factors related to human error

²⁷⁶ Known in the aviation community as the *Accident Chain*.

are the most frequently cited in accidents. Studies have implicated human error in accidents across virtually all occupations, with 70-80% involvement for civil and military aviation (O'Hare, Wiggins, Batt, & Morrison, 1994; Shappell & Wiegmann, 2001; Wiegmann & Shappell, 1999, 2001; Yacavone, 1993). Additional work has shown while the aviation accident rate attributable entirely to mechanical failure has decreased noticeably over the past decades, the rate attributable at least in part to human error has declined at a slower rate (Wiegmann & Shappell, 2003).

While automation in aviation, including military aviation, has greatly improved performance and safety by reducing pilot workload (Lowy, 2013), human error remains a significant causal factor in accidents (Rash, 2012). Even with the increasing dependence on computer systems, pilots rely heavily on vision for situation awareness in and out of the cockpit. While pilot certification requires a minimal level of visual performance (see *Color Vision Tests and Standards* section), the complexities and limitations of human vision in flight operations are frequently “understated, neglected, or overlooked by most pilots” (Gibb, Gray, & Scharff, 2010).

Vision is arguably the most dominant of all of the human senses. As previously stated, the visual sense is the most complex of the human sensory systems (Grady, 1993; Jonas, Schmidt, Muller-Bergh, Schldrzer-Schrehardr, & Naumann, 1992). So, it is not surprising vision is a pilot's most important sense, used to obtain information during flight, from both in and out of the cockpit.

A number of factors can impact pilot visual performance during flight. These include problems related to the function of the eye (e.g., refractive error and color deficiencies), as well as age-related changes in function (e.g., presbyopia and cataract formation). There are also self-imposed factors (stressors) such as sleep deprivation, fatigue, use of prescription or over-the-counter medications, alcohol and tobacco use, dehydration, and low blood sugar (Rash et al., 2010). Environmental factors include illumination level (and related dark adaptation level), atmospheric clarity (e.g., weather conditions), and noise. In addition, special flight conditions such as presence of hypoxia and use of night-imaging systems flying impact visual performance.

Pilots, like all humans, have been “seeing” all their lives and resolutely “believe what they see,” or at least what they think they see (Gibb, Gray, & Scharff, 2010). When the brain receives information from multiple senses and there is not agreement amongst these inputs, misperceptions (illusions) can result. One example, the pitch-up illusion, can occur during a rapidly-accelerated take off. The somatosensory system signals the aircraft is pitching up, and without good visual references, the pilot pushes forward on the control stick to counteract this perceived motion. This action can result in a descent and crash.

One distinct group of such illusions is *visual* illusions, which include false horizon, autokinesis, vertigo, false perception of distance, and black hole approach (see *Visual perception* section). A special vision-linked illusion is spatial disorientation, defined as a situation where the pilot is unable to correctly perceive motion and position in relation to the surrounding environment. Spatial disorientation is more likely to occur at night, in bad weather, in instrument

meteorological conditions (IMC),²⁷⁷ and when there is no visible horizon. The “graveyard spin” is an example, where a false perception of rotation is caused when a spin suddenly stops and the pilot perceives a spin in the opposite direction – causing the pilot to make control inputs to re-enter the original spin (FAA Civil Aerospace Medical Institute, 2016).

The U.S. Army’s continuing shift to night operations with its obligated use of night imaging systems (e.g., ANVIS/NVG and the AH-64 HMD) brings to the forefront a special class of problems and illusions. While permitting flight throughout the night, these systems present the pilot with less than perfect visual cues for pilotage. Compared to a pilot flying under day-visual flight rules (VFR) conditions,²⁷⁸ the pilot using a night-imaging system is handicapped in visual acuity, field-of-view, color vision, and depth perception (Price & McLean, 1985; Parush, Gauthier, Arseneau, & Tang, 2011). Other problems can include ocular rivalry (with monocular displays), additional head-supported weight, and the stresses of disrupted circadian rhythms inherent in nighttime operations (Crowley, 1991). Of particular note is imagery presented by these systems is monochromatic, green at a wavelength of 545 nm (P-43 phosphor) (see *Achieving color in displays* section). Visual issues associated with this monochromaticity already have been discussed (see *Night imaging technology in Army aviation* section).

Degraded visual cues present with the use of these systems, combined with stressful and fatiguing flight profiles, predispose aviators to visual illusions and errors that may result in accidents (Vyrnwy-Jones, 1988; Braithwaite, Douglass, Durnford, & Lucas, 1998). One summary of U.S. Army aviation accidents occurring over a 10-year period from 2000 through 2009 reported a total of 1224 accidents²⁷⁹ with 241 (20%) when night-imaging systems were in use (Bambarger, 2010).

The illusions (misperceptions of reality) occurring when using HMDs and NVGs are often not unique to these devices, but the effects of these illusions may be exacerbated because of certain characteristics of HMDs and ANVIS/NVGs. (Crowley, 1991; Crowley, Rash, & Stephens, 1992).

Common misperceptions when using ANVIS/NVGs include those of motion, depth, slope, and distance estimations (Temme et al., 2010). The misperception of depth is probably one of the most commonly reported illusions when using ANVIS/NVGs (Crowley, 1991; U.S. Army Safety Center, 1991; Miller and Tredici, 1992). Although not unique to NVGs, their use does increase the probability and, perhaps, the severity of the misperception of depth during flight. The characteristics of NVGs exacerbating the misperception of depth include:

- Reduced visual acuity (thereby reducing stereopsis capability [Wiley, 1989] and reducing texture gradient perception [Miller & Tredici, 1992])
- Lack of color (reduces aerial perspective)
- Potentially unbalanced light levels in the two channels (causing the Pulfrich effect [Crowley, 1991; Pinkus & Task, 2004])

²⁷⁷ Instrument meteorological conditions (IMC) is an aviation flight category that describes weather conditions that require pilots to fly primarily by reference to flight instruments.

²⁷⁸ Visual flight rules (VFR) are a set of regulations under which a pilot flies an aircraft in weather conditions generally clear enough to allow the pilot to see where the aircraft is heading.

²⁷⁹ This report combines combat, training, and test flights and includes eight years of wartime operations.

- Limited field-of-view (reduces geometric perspective)
- Elimination of the physiological link between accommodation and convergence. Accommodation depends on the NVG eyepiece setting, whereas convergence depends on the distance of the object being viewed and the NVG input/output optical axes alignment (Miller and Tredici, 1992)

The only additional HMD presenting flight imagery fielded in U.S. Army aviation is the IHADSS HMD (Figure 1, p. 2, bottom, right) used in the AH-64 Apache helicopter.²⁸⁰ Since the IHADSS is a monocular device, none of the binocular-based illusion mechanisms encountered with the ANVIS/NVGs can occur. However, its monocular design introduces new perceptual issues (Hiatt, Rash, & Heinecke, 2008; Rash, 2008). With the IHADSS, the pilot views, via the display optics, aircraft parameter symbology along with the sensor imagery through the right eye and has the left eye unaided and free to view either inside or outside the cockpit (e.g., interface with cockpit instruments, map reading, and observing visible images outside the cockpit). This monocular design also can cause the complete loss of stereopsis (3D vision secondary to the presence of binocular vision) during night flight when the bright FLIR imagery is delivered to the right eye only. Stereopsis is particularly important in tactical helicopter flight (e.g., combat maneuvering and NOE flight). However, monocular depth cues (e.g., retinal size, motion parallax, interposition, and perspective) are generally accepted as more important for routine flight. Pilots can improve their non-stereo depth perception with training. Nevertheless, AH-64 pilots have reported a reduction in monocular cues, most likely due to the reduced resolution of the FLIR sensor/IHADSS display system (Rash et al., 1998; Rash, 2000).²⁸¹

Most of the studies involving pilot complaints and problems with the monocular IHADSS were conducted in peace time. However, an opportunity to investigate IHADSS use in combat arose with the onset of Operation Iraqi Freedom (OIF) in 2003. In a survey of 40 pilots who had returned from OIF, the two most reported static illusions were faulty height judgment and faulty slope estimation (Rash & Hiatt, 2005). Although both of these illusions can occur without the IHADSS, they are most likely enhanced by the IHADSS because of the reduced visual acuity (approximately 20/60 Snellen), limited field-of-view, the monocular viewing (as opposed to binocular), and possible slight errors in view angle between the pilot's line of sight (through the image) and the sensor's direction of view (where the sensor is pointed). Also, with the sensor mounted on the nose of the aircraft, exocentrically from where the pilot's eyes, the pilot must cognitively compensate for the shifted view point, which can lead to height and slope misperceptions. The two most reported dynamic illusions in the same survey were undetected drift and faulty closure judgment.

The only study investigating the possible role of the IHADSS HMD and PNVs pilotage sensor may play in U.S. Army AH-64 Apache accidents was conducted in 2003 (Rash, Reynolds, Stelle, Peterson, & Leduc, 2004). A review of accidents reported for the period from 1985 to 2002, concluded dynamic illusions are particularly important when using the Apache's IHADSS HMD. Of the 228 reported AH-64 accidents, approximately 93 (41%) involved the HMD in some way, and for 21 of these, the HMD and PNVs sensor played a role in the accident sequence itself. Furthermore, the most frequent causal factor in all of the accidents studied was

²⁸⁰ An ANVIS-HUD, providing symbology, is flown in UH-60 and CH-47 aircraft. Its day configuration, providing symbology only, attaches to the ANVIS helmet mount; the night configuration adds symbology to the I² imagery.

²⁸¹ This issue has been greatly mitigated by the fielding of the improved M-TADS sensor.

the presence of dynamic (motion-based) illusions, which were identified as disorientation (14%), illusory drift (24%), faulty closure judgment (10%), and undetected drift (24%). The relatively important role of dynamic illusions reported in these accidents suggests the illusions associated with motion perception warrant special attention. The investigation reported the second most frequent cause was degraded vision (i.e., reduced resolution and contrast). This is consistent with the presence of static illusions, i.e., the more sparse or degraded the visual stimulus field, the more pronounced are the illusory percepts. Nevertheless, the absence of an accident does not mean the pilot had no visual illusions, since pilots routinely and successfully control aircraft in the presence of multiple visual illusions.

Color as an accident causal factor in aviation has historically been associated with external lighting, either used for marking runways (including glide slopes) or for identification of obstructions (e.g., towers and antennae). Sometimes, crew CVDs are cited. Such was the case in the now infamous 26 July 2002 Federal Express (FedEx) Flight 1478 Boeing 727-232 accident in Tallahassee, Florida. The aircraft crashed on final approach at night well short of the runway. The captain, first officer and flight engineer were seriously injured, and the airplane was destroyed by impact and resulting fire. In its final report, the NTSB stated “the probable cause of the accident was the failure of the captain and first officer to establish and maintain a proper glide path during the night visual approach to landing. Contributing to the accident was a combination of the captain's and first officer's fatigue and failure to adhere to company flight procedures, the captain's and flight engineer's failure to monitor the approach, and the first officer's color vision deficiency” (National Transportation and Safety Board [NTSB], 2004). In the investigation narrative it was stated the runway did not have an ILS, but did have a PAPI, a series of red and white lights aiding flight crews in determining if they are on a proper glide slope to the runway, too high or too low (see *Exterior use of color* section). The NTSB found the first officer, who was the flying pilot, had a history of CVD, for which he had a waiver from the FAA. Extensive post-crash evaluation of the first officer's color vision concluded this deficiency would likely have interfered with his ability to discern the differences between the white and red lights that give the pilots their altitude clues.

At the time of the investigation of the FedEx accident, the NTSB had identified only two other accidents (one civilian and one military) involving pilots with valid medical qualifications in which a CVD was cited as a contributing cause (Werfelman, 2008). One was an Aug. 29, 1992, incident (NTSB No. CHI92LA259) in which the pilot of a Mooney 20F with “a waiver for partial color blindness to red and green” landed on a closed runway marked with orange crosses in the dirt 50 feet (15 meters) beyond each end. The pilot’s “limited ability to detect the orange-colored marking” was cited as a contributing factor, along with his anxiety following a near-midair collision that preceded the landing. The other incident involved a Navy F4J lost on Aug. 5, 1980 (NTSB, 2004), “when a severely color deficient pilot failed to interpret correctly the colored navigation lights of other aircraft in the area, leading to the false impression of a collision.”

NTSB accident/incident database.

To begin investigating the potential role of color inside the cockpit in U.S. Army aviation accidents, it was decided to look first at the NTSB aviation accident database for civil (non-

military) aviation, expecting any potential issues to be easier to identify in such a larger database. While the NTSB database does not categorize accidents by casual factor, it does provide a narrative stating the conclusions of the accident investigation where sufficient data are available to assign responsibility. The first search looked at the 10-year period of 1 Jan 2007 to 31 Dec 2016 and used the whole keyword “color” as the search term.²⁸² The search was confined to accidents/incidents occurring within the US and for all flight operation categories. The search was conducted in two phases: first for airplane only (fixed-wing aircraft) and then helicopter only (rotary-wing aircraft) categories, excluding amateur built. The searches were limited to the “Factual cause” reports. Each of the report narratives were examined first for investigator mentioning of the whole keyword “color” in any regard and second for “color” having a role in the event.²⁸³ The searches returned 545 and 77 accident/incident events for airplane and helicopter categories, respectively.²⁸⁴ Before summarizing these events, it is important to emphasize the presence of the search keyword in an accident investigation report does not imply an association of color to the accident event.

Of the 545 identified airplane events, the most common presence of the search term “color” (229 events; 42%) involved descriptions of the color of spark plug electrodes. The next most common occurrence (131 events; 24%) was associated with the color of fuel samples. This is not surprising as the NTSB’s Aviation Investigation Manual’s checklist (NTSB, 2002) calls for these two physical examinations (i.e., following an accident, spark plugs are to be removed from the engine for examination, and fuel samples are to be obtained). In the case of spark plugs, the electrodes will be gray or light tan (depending on type) if in normal state; dark tan or brown can indicate combustion deposits; and black can indicate soot from lead/carbon fouling from a too rich fuel/air mixture (Santerre, 2007). For the examination of fuel samples, color can indicate correct/incorrect fuel type and/or contamination. Blue would be the correct color for the fuel grade used in many piston engine aircraft and straw or clear for turbine/diesel aircraft. Since use of the correct fuel is critical, dyes are added to help identify the type and grade of fuel. Care must be exercised to ensure the correct aviation grade is being used for the specific type of engine. Since use of the correct fuel is critical, dyes are added to help identify the type and grade of fuel (Flightlearnings.com, 2010). The fuel color code is shown in Figure 191. It was common for an event to have “color” present for both of these investigative elements.



Figure 191. Color code for aviation fuel.

²⁸² Search was conducted on 25 July 17 and included only events as of 31 December 16 that had completed or preliminary investigation narratives.

²⁸³ The words “colored,” “discoloration” and “discoloring” were allowed as a countable event as the terms imply color being observed.

²⁸⁴ Midair collisions are counted as 2 events.

While this section is biased towards color as a causal factor in accidents, NASA research pilot R. Ranaudo gives an example where the presence of fuel color coding prevented an accident (personal communication, September 15, 2017):

I have had an experience where color association prevented a fatal accident, of which I would have been involved. We were refueling our NASA research aircraft after a long flight over the Arctic sea at Inuvik, AK. When taxiing to the gas pumps, we radioed the FBO and specifically asked for AVGAS. They directed us to the pumps. It was extremely cold and because the engines were large reciprocating (2000hp) types, we had to complete fueling quickly and get them restarted as soon as possible. There were huge mounds of plowed snow all around the gas pumps obscuring the pumps and fuel hoses. The pump boy assisted our crew chief on the wing during fueling. From the cockpit, we noted the only pump cover we could actually see was yellow. Green is for AVGAS. Unknown to us, they were pumping Jet Fuel into the tanks. Had we not asked twice what fuel was going into the wings, we would have tried to take off with jet fuel and both engines would likely have failed right after takeoff at Max gross weight. After washing through all the jet fuel in the wing, we finally got started and took off uneventfully. This is where color association actually prevented an accident that could have been fatal for all of us on board.

The other color occurrences can be loosely categorized as follows (with examples):

- External to aircraft, e.g., terrain feature color, transmission wires, skid marks on runway, runway concrete, fuel truck, and cellular tower
- Aircraft exterior, e.g., airframe paint color scheme and markings, and wheel temperature stickers
- Aircraft interior, e.g., torque seal, wire insulation, and sealant material
- Cockpit display related, e.g., color code on Electronic Centralized Aircraft Monitor (ECAM) display, colored landing gear indication system, color MFDs, color GPS electronic map devices, and Terrain Awareness and Warning System (TAWS)
- Lighting, e.g., runway lighting, landing gear lights, and navigation lights
- Lubricates and other non-fuel fluids, e.g., brake fluid and oil
- Crash related, e.g., glass lens fragments of navigation lights, smoke, fire, witness marks indicating wire strike, paint transfer (to/from airframe or propeller), and propeller blade scratches
- Presence or lack of presence of discoloration due to rust, deposits, and heat effects) on engine components, e.g., brake assembly, carburetor, crankshaft connecting rods, drive gear, exhaust manifolds, exhaust pipe interiors, flange gasket, fuel diaphragm, fuel pump box, horizontal stabilizer, landing gear strut, magneto, muddler assembly, oil sump bearings, piston rods, propeller hub, pushrods, slip joints, and valve covers²⁸⁵
- Contaminants, e.g., in the oil pan sump and fuel strainer filter

²⁸⁵ Most of the defects found on aircraft are found by visual inspections"; the main three types being cracks, disbanding, and corrosion (U.S. Department of Transportation, 1997).

It is important to note the presence of the search keyword does not imply color as a factor in the accident event, as many occurrences were due to inclusion of manufacturer data, e.g., statements of display and GPS color schemes.

Of the 545 identified airplane events, only one event (NTSB No. CEN10CA332) resulted in a determination of color as a contributing factor. In this event, the pilot/owner and a commercial-rated pilot departed in a tandem, two-seat, tailwheel-equipped airplane on a local flight. On the return leg to the airport the commercial pilot was flying the airplane. The commercial pilot, who was seated in the rear seat, did his before-landing checks to set up for the landing; however, during the approach to the runway the engine lost power. Unable to regain engine power, a forced landing in a vacant lot was attempted. During the forced landing the airplane sustained damage to the left wing and fuselage. After the accident it was discovered the engine's fuel shut-off valve was in the (pulled) off position. The commercial pilot reported he flew a Cub Special (PA-11), but never the accident airplane (J3), and the fuel shut-off valve in the J3 was in the same place as the carburetor heat in the PA-11. The commercial pilot added the shut-off valve was not color coded or marked, and he pulled the fuel shut-off knob mistaking it for the carburetor heat. It was determined that contributing to the accident were the unmarked (uncolored) fuel shutoff valve and the pilot's inexperience in the accident airplane.

In addition to this event, ten other events are summarized in Table 18. Although not cited for color as a causal factor, these additional events are presented because a color association was present in the investigation report narratives, and the associations can be related to a number of color principles discussed throughout this paper. As one example (NTSB No. ERA09LA111 and ERA10LA098), *in situ* airspeed indicator markings and color code range indicators in two different, but same model, accident aircraft were different from those shown in the airplane manufacturer's documentation. In both events, the investigation reports did cite as a contributing factor the improperly marked airspeed indicator but did not cite the different color scheme itself as a factor.

In another example (NTSB No. WPR10LA252), on a cross-country flight in which the pilot had landed, attempted to repair a fuel valve that prevented the change from an almost empty left fuel tank to a full right fuel tank, attempted to resume flight but lost engine power following takeoff and crashed. While not determined to be a factor, the investigation report included photographs taken after the accident (as well as a note on the pilot's kneeboard) indicating the airspeed indicator color arcs were not marked as required (i.e., missing color). An example of these color arcs (on a multi-engine aircraft) is shown in Figure 192. The missing color arcs were not cited as a factor in the accident.

The selected events with color association presented to Table 18 primarily dealt with color attributes of components, e.g., displays and lighting. The keyword "color" also appeared in the 18 event narratives in association with pilot color vision. Eighteen events referenced CVDs and/or restrictions for flight under color signal control. These events are listed in Table 19. In most of the events, the pilot was flying with a known (waivered or restricted flight) color deficiency. In eight of these events, the pilot's certificate had been restricted from flying at night or under color signal control. In two events (NTSB No. ERA12FA566 and ERA13FA225), the pilots had been issued a Statement of Demonstrated Ability (SODA) for defective color vision

Table 18. Selected results of 10-year search of NTSB aviation accident database using “color” as search keyword.

Event date	Aircraft Make/Model	NTSB No.	Event severity
23 DEC 08	CZECH AIRCRAFT WORKS SportCruiser	ERA09LA111	Injuries (1)
<u>Color association:</u> Examination of photographs following a collision with terrain during takeoff revealed the installed airspeed indicator's markings and airspeed <u>color</u> code range markings were different from those shown on the airplane manufacturer's website for their standard installation. The investigation report cited as a contributing factor the improperly marked airspeed indicator and the airplane manufacturer's improper airspeed indicator information. However, the presence of <u>color</u> itself was not a factor.			
19 OCT 09	BOEING 767	OPS10IA001	Injuries (194)
<u>Color association:</u> Fatigued pilots at the end of a long-distance flight aligned with incorrect taxiway. The runway lighting configuration included blue LED lights on the edges of one taxiway from the east end to another taxiway having incandescent lighting on its edges running west of it. Although incandescent and LED lights of the same <u>color</u> and intensity will test in the same <u>color</u> and brightness range, the LED type lights are perceived by the human eye to be brighter than incandescent lights when in clear visibility. The pilots noted difficulty in identifying between white incandescent and blue LED lighting. The investigation report cited as a contributing factor the mixing of lighting technologies, but did not specifically identify a <u>color</u> perception component.			
21 DEC 09	CZECH AIRCRAFT WORKS SportCruiser	ERA10LA098	Injuries (2)
<u>Color association:</u> While performing slow-flight maneuvers, the pilot attempted to perform a power-off stall. At the onset of the stall, the pilot added power, the airplane yawed left, and “snapped” into a tight spin to the left. Recovering was attempted, but during the post-spin dive recovery, the airplane struck trees and terrain, and came to rest inverted. An examination of the airplane revealed the airplane's airspeed indicator's <u>color</u> code range markings were inaccurate and did not agree with the information published in the manufacturer's Pilot Operating Handbook (POH). As with the similar accident presented above (23 DEC 08, ERA09LA111), the investigation report cited as a contributing factor the improperly marked airspeed indicator and the airplane manufacturer's improper airspeed indicator information. However, the presence of <u>color</u> itself was not a factor.			
31 MAR 10	BEECH 95-B55 (T42A)	ERA10CA201	Injuries (3)
<u>Color association:</u> While conducting touch-and-go landings, the pilot “mistook the gear lever for the flaps,” and the landing gear began to retract. While recovering, the right propeller struck the ground and the airplane spun to the right and came to rest upright in a grassy area between the runway and taxiway. The airplane's landing gear and flap control levers were the same <u>color</u> and approximately the same size, but were located on opposite sides of the control column. The probable cause of this accident was cited as the pilot's inadvertent retraction of the landing gear on the ground during a touch-and-go. However, while noted, the issue of same <u>color</u> was not cited as a factor.			

after passing a signal light test. In one event (NTSB No. ERA14LA057), the pilot had passed an operational color test after failing color vision testing four months earlier. And, in another event (NTSB No. CEN15FA305), it was determined the pilot had a change in his color vision due to medication use. However, in none of the 18 events described was flying with a color deficiency or with a color signal restriction cited as a causal factor.

Table 18 (continued). Selected results of 10-year search of NTSB aviation accident database using “color” as search keyword.

Event date	Aircraft Make/Model	NTSB No.	Event severity
5 APR 10	AIRBUS 320	ENG10IA026	None
<u>Color association:</u> An Airbus A320 airplane experienced a left engine fan cowl separation during takeoff. The latch assembly is normally weighted and the inside and the sides of the latch handle are painted a different <u>color</u> (typically red or orange) than the cowling skin to visually highlight whether the latch is fully locked or not. This safety feature was negated when mechanics placed the latch assembly up against the housing. In this position, the latch is neither latched nor locked but the latch assembly may be flush with the cowling such that the paint on the latch assembly handle is not visible, giving a false indication the latch is properly locked. The investigation report cited the design of the fan cowl latch assembly that can provide a false latch condition when the latch is neither latched nor locked. <u>Color</u> was not a direct factor.			
21 MAY 10	Luscombe Silvaire S-LSA-8C	WPR10LA252	Injuries (2)
<u>Color association:</u> On a cross-country flight with full fuel in the left and right tanks and with the left fuel tank selected, the pilot was unable to change from the almost empty left fuel tank to the full right fuel tank. The pilot landed and attempted to repair the fuel valve. After takeoff, the engine started to lose power again. The pilot attempted to turn back to land in the field again, but the airplane pitched down in a left turn and impacted the ground. While not determined to be a factor, the investigation report included photographs taken after the accident (as well as a note on the pilot's kneeboard) indicating the airspeed indicator <u>color</u> arcs were not marked as required (i.e., missing <u>color</u>). An example of <u>color</u> arcs on a multi-engine aircraft is shown in Figure 192. The missing <u>color</u> arcs were not cited as a factor in the accident.			
14 JUN 10	PIPER J3C-65	CEN10CA332	Injuries (2)
<u>Color association:</u> The pilot/owner and a commercial-rated pilot departed in a tandem, two-seat, tailwheel-equipped airplane on a local flight. During the landing approach the engine lost power. Unable to regain engine power, they elected to conduct a forced landing in a vacant lot. During the forced landing the airplane sustained damage to the left wing and fuselage. After the accident the pilot/owner and commercial pilot discovered the engine's fuel shut-off valve was in the (pulled) off position. The commercial pilot reported he flew a Cub Special (PA-11), but never the accident airplane (J3), and that the fuel shut-off valve in the J3 was in the same place as the carburetor heat in the PA-11. The commercial pilot added the shut-off valve was not <u>color</u> coded or marked, and that he pulled the fuel shut-off knob mistaking it for the carburetor heat. It was determined that contributing to the accident were the unmarked (<u>uncolored</u>) fuel shutoff valve and the pilot's inexperience in the accident airplane.			
2 JUL 10	BEECH E-55	WPR10LA347	Injuries (5)
<u>Color association:</u> The pilot reported that upon entering the traffic pattern to land and while extending the landing gear, the airplane started vibrating. The pilot stated he confirmed the "GREEN" light was on, which indicated to him that the landing gear was down and extended; a post-accident examination of the landing gear system revealed that the <u>color</u> of the gear down light is BLUE. The pilot reported he also confirmed that the red arrow indicator was pointing down, which indicated the landing gear was down and extended. <u>Color</u> was not cited as a contributing factor.			

Table 18 (continued). Selected results of 10-year search of NTSB aviation accident database using “color” as search keyword.

Event date	Aircraft Make/Model	NTSB No.	Event severity
24 SEP 11	CESSNA 120	ERA11LA503	Fatal (1)
<u>Color association:</u> The airplane was equipped with two 12.5-gallon fuel tanks. Direct reading fuel quantity gauges were installed in the tank, at the wing root, which the pilot could observe from the cockpit. The gauges operated mechanically and did not feature any provisions for lighting. The gauges were placarded with graduations noting F [full], 3/4, 1/2, and 1/4 tank capacity. The area below the 1/4 marking was shaded red in <u>color</u> with the marking, "NO TAKE OFF." Probable cause of this accident was determined to be loss of engine power due to: “The pilot's inadequate fuel planning, which resulted in a total loss of engine power due to fuel exhaustion.”			
16 MAY 13	CIRRUS SR22	CEN13IA285	Injuries (1)
<u>Color association:</u> Pilot reported that he experienced a loss of control of the airplane based upon instrument indications, the airplane bouncing, and that the horizontal situation indicator (HSI) was spinning in circles. He said there was a HSI flux gate excitation failure message, the HSI turned red, the HSI card started turning in circles, and there was an "X" at the bottom of the HSI, which he said meant that heading information was not being received. There were no annunciations, cautions, or warnings, only the flux gate excitation message. There were no problems with the MFD. The attitude indicator appeared as if it was caged or stuck and was not moving around as the airplane “porpoised.” He said the blue and brown <u>colored</u> segments of the attitude indicator formed an "X." The brown portion was on the bottom, and the blue portion was on the top. He said he knew the airplane was in level flight at the time of this attitude indication. The airplane's wet compass was not spinning. When the pilot was asked how he knew the airplane attitude was not being displayed correctly on the attitude indicator, he said he does not know and it was based on his memory. The investigation report did not associate attitude indicator <u>color</u> with any casual finding.			



Figure 192. Example of multi-engine airspeed indicator (ASI) showing color arcs. The color codes are: White Arc, Green Arc, Yellow Arc, Red Radial Line, and Blue Radial Line.

Table 18 (continued). Selected results of 10-year search of NTSB aviation accident database using “color” as search keyword.

Event date	Aircraft Make/Model	NTSB No.	Event severity
29 JUN 16	BEECH E-90 King Air	CEN16LA247	Injuries (1)
<u>Color association:</u> A skydiving airplane was struck by an exiting skydiver. The jump indication lights are controlled by a rotary switch on the cockpit pedestal. There is one indication light on the pedestal and one light next to the jump door for the skydivers to see. When the light is off or red there are to be no jump activities. The amber light indicates the door can be opened to spot check the area. The green light indicates it's safe to jump. The lights can be viewed from anywhere in the airplane, unless another skydiver is blocking the view. At 5,000 feet AGL, the pilot configured the airplane for a jump and activated the jump indication lights. The student and one other skydiver safely exited the airplane at that time as "hop and pop" jumpers. The pilot de-configured the airplane and initiated a climb to the planned jump altitude. The pilot did not recall any jump indication lights being illuminated in the cabin during the climb and none of the remaining jumpers notified him of any illuminated jump lights. He continued the climb to 16,000 feet mean sea level, which was 1,500 feet below normal exit altitude. At 12.2 nautical miles from the intended GPS waypoint, the pilot maintained a full power setting and continued the climb for 17,500 feet mean sea level. The pilot stated he activated the amber light, which indicated the skydivers could open the door and spot check the area. Prior to reaching the jump location, he was in the process of configuring the airplane for the jump when he felt the flight controls shake, but the flight instruments appeared normal. He then felt a jolt in the flight controls and heard a "thud" sound. He looked back and noticed 3 skydivers had exited the airplane and 3 more were in the process of exiting. He switched the jump lights to red and instructed the remaining skydivers to remain in the airplane. The remaining skydivers told the pilot someone had hit the tail. Another skydiver who was positioned near the pilot during the flight stated they were on "what appeared to be a jump run" when the door was opened and the first group climbed out of the airplane. When the first group jumped, the airplane was flying faster than normal based on the sound of the jumpers' exit. He noticed the flap were retracted and another skydiver asked him if a "dent was always in the tail?" A second group of skydivers exited the airplane, and then the door was shut. He did not see the jump indication light <u>color</u> during the accident. Several others onboard mentioned the yellow indication light had been on since the "hop and pops" had exited, then the light was green before the first group of three exited. NTSB personnel did not travel to this accident. No determination of causal factors was made.			

Of the 77 helicopter events, the vast majority contained references to color involving fuel and lubrication contaminants, paint transfer from collisions with ground objects, residue on cables and engine components, color coding of main rotor blades for maintenance purposes, colored rotor blade leading edge wear strips, fire damage discoloration, part identification, or exterior paint color. Five of the events mentioned the presence of a GPS moving-map color display, but all of these were related to the removal of flight data during the accident/incident investigations. However, three events did relate directly or indirectly to color use to the cockpit. These three events are summarized with a description of color association in Table 20. In only one of these events (NTSB No. CEN09MA117) was a color warning indicator implied as a contributing factor. This involved the presence of a red color bar indicating a low-rotor-speed condition, which was not coupled to any other alert and apparently was not “seen” by the crew.

Table 19. Results of 10-year search of NTSB aviation accident database using “color vision” as search keyword.

Event date	Aircraft Make/Model	NTSB No.	Event severity
9 NOV 08	PIPER PA-32S-300	WPR09FA034	Fatal (4)
Pilot had a known <u>color</u> vision deficiency. (The report did not indicate if the pilot had been issued a waiver or flight limitation.) The accident forces prevented the evaluation of any pre-existing conditions, and it was unclear what, if any, relevance the pilot’s <u>color</u> vision deficiency had to the accident.			
11 JUN 10	PIPER PA-32R-300	WPR10FA287	Fatal (4)
The pilot had been issued a third-class airman medical certificate on December 17, 2008, with a "miscellaneous restriction assigned." According to the FAA, the restriction assigned to the pilot was "not valid for night flying or by <u>color</u> signal control" and was re-evaluated on August 14, 2009, following a medical flight test. The pilot was subsequently granted a "third-class letter of evidence" upon successfully completing a signal light gun test. This was not determined to be a contributing factor.			
17 NOV 10	AMERICAN CHAMPION AIRCRAFT 8GCBC	WPR11FA061	Fatal (1)
The pilot, age 74, held an airline transport pilot certificate with an instrument rating. His most recent FAA third class medical certificate was issued in September 2010 (two months before the accident) with three limitations: must wear corrective lenses, not valid for night flying, and not valid to fly by <u>color</u> signal. This was not determined to be a contributing factor.			
15 SEP 11	REMOS GMBH	CEN11FA645	Fatal (2)
Pilot certificate was not valid for flying at night and for <u>color</u> signal control. This was not determined to be a contributing factor.			
29 NOV 11	PIPER PA-31	CEN12FA088	Fatal (1)
After a decade of being restricted from night flight and <u>color</u> signal control, pilot passed Ishihara <u>color</u> plate test and failed to report medical status for ensuing decades. His possible <u>color</u> vision deficiency was not determined to be a contributing factor.			
11 MAY 12	CESSNA 401	CEN12FA290	Fatal (4); Injuries (1)
On June 28, 2011, a first class medical certificate was issued with the restriction “not valid for night flying or by <u>color</u> signal control.” This was not determined to be a contributing factor.			
7 SEP 12	GOODYEAR F2G	CEN12LA615	Fatal (1)
Pilot had a waiver for <u>color</u> vision deficiency. This was not determined to be a contributing factor.			
17 SEP 12	MOONEY M20M	ERA12FA566	Fatal (2)
During the most recent as well as previous examinations, the pilot failed <u>color</u> vision testing, specifically noted in 1998 as being unable to distinguish between red and green. On July 14, 1998, the pilot was issued a SODA for defective <u>color</u> vision after passing a signal light test. This was not determined to be a contributing factor.			
19 DEC 12	BEECH B100	WPR13FA073	Fatal (2)
The pilot’s previous student pilot medical certificate indicated he was <u>color</u> blind, and it listed limitations for flying at night and for using <u>color</u> signals. It was determined the pilot’s improper decision to fly at night with a known visual limitation (night vision) was a contributing factor. Color deficiency was not listed as a contributing factor.			
27 FEB 13	CESSNA 150M	CEN13LA179	Fatal (1)
Pilot was issued a waiver for defective <u>color</u> vision after passing the Aviation Signal Light Test. This was not determined to be a contributing factor.			

Table 19 (continued). Results of 10-year search of NTSB aviation accident database using “color vision” as search keyword.

Event date	Aircraft Make/Model	NTSB No.	Event severity
2 MAY 13	GRUMMAN G-44	ERA13FA225	Fatal (1)
Pilot possessed a SODA for defective <u>color</u> vision. This was not determined to be a contributing factor.			
30 NOV 13	PIPER PA-28-161	ERA14LA057	Fatal (1)
Pilot passed operational <u>color</u> test after failing <u>color</u> vision testing 4 months earlier. This was not determined to be a contributing factor.			
3 FEB 14	CESSNA 525	CEN14LA129	Injuries (7)
The pilot’s second-class medical certificate, which had been issued more than 20 months before the accident, had expired. The medical certificate limitation section in the expired certificate stated, “Not valid for night flying or by <u>color</u> signal control.” This was not determined to be a contributing factor.			
14 JUN 15	GRUMMAN AA-5	CEN15FA269	Fatal (1); Injuries (1)
The pilot's most recent FAA third-class medical certificate was issued on May 22, 2014 (~13 months prior to accident), with the limitations that he was prohibited from flying at night and by <u>color</u> signal control due to <u>color</u> blindness. This was not determined to be a contributing factor.			
25 OCT 14	STOL UC 1	CEN15LA038	Nonfatal
Pilot possessed a <u>color</u> vision waiver. This was not determined to be a contributing factor.			
14 JUL 15	PIPER PA-32-300	CEN15FA305	Fatal (2)
It was determined the pilot had a change in his <u>color</u> vision due to medication use: Vardenafil, an oral medication used to treat erectile dysfunction, which carries a warning about the potential for temporary changes in <u>color</u> vision but no warnings about performance impairment following use. The investigation did not list this medication use as a contributing factor.			
9 NOV 15	CIRRUS DESIGN SR22	CEN16FA034	Fatal (2)
The pilot was issued a third class medical certificate on November 4, 2013 (2 years prior to accident). The certificate contained the limitation "Not valid for night flying or by <u>color</u> signal control. Must wear corrective lenses." This was not determined to be a contributing factor.			
6 JUN 16	ROCKWELL S2R	WPR16FA120	Fatal (1)
The pilot held a commercial pilot certificate with an airplane single-engine land rating and a second-class airman medical certificate issued on January 12, 2016, with the following limitations: "Not valid for night flying or by <u>color</u> signal control. Not valid for any class after January 31, 2017." This was not determined to be a contributing factor.			

The two other color-related events are mentions of color lamp filters (NTSB No. CEN12FA091) and the inability to identify the color of an instrument light (NTSB No. ERA09LA360). One accident event (NTSB No. ERA11FA101A/B) was a midair collision between a fixed-wing Cessna 172H and a rotary-wing Eurocopter Deutschland GMBH EC 135 P2 and is represented in both the NTSB airplane and helicopter event counts.

Included in Table 20 are two additional events that while not integral to the aircraft cockpit are related to human interaction with color. The first (NTSB No. WPR12GA106) is demonstrative of the HF failure of relying on color as the only display feature. This involved the Automated Flight Following (AFF) system that automatically transmits the location, altitude, course, and speed of an aircraft through commercial satellite segments. In this event, the AFF

Table 20. Summary of NTSB aviation database helicopter category accidents/incidents with pertinent color association.

Event date	Aircraft Make/Model	NTSB No.	Event severity
4 JAN 09	SIKORSKY S-76C	CEN09MA117	Fatal (8)
<u>Color association:</u> The primary cause of the accident was the sudden loss of power to both engines that resulted from impact with a bird. The helicopter's integrated instrument display system (IIDS) provides the flight crew with engine and main rotor system performance information. Three IIDS screens are mounted in the instrument panel; one in front of the captain, one in front of the co-pilot, and one in the center of the instrument panel (the main rotor number of rotations [Nr] information is only displayed on the pilot's and copilot's IIDS.) The Nr data is provided to the flight crew by a broad <u>color</u> bar on the right side of the IIDS presenting as green, yellow, or red (which warns the flight crew of a critical, unsafe flight conditions requiring immediate action). The helicopter was not equipped with an audible alarm or a master warning light to alert the flight crew of a low Nr condition. Investigators listed as a contributing factor the lack of a master warning light and audible system to alert the flight crew of a low-rotor-speed condition. The implication is the crew may not have perceived the red <u>color</u> bar on the IIDS.			
21 JUN 09	ROBINSON R22	ERA09LA360	Injuries (2)
<u>Color association:</u> Following detecting a vibration in the tail rotor, the pilot decided on a spot to autorotate into. He noticed the clutch light was on and one other light, but wasn't sure which light it was, it's <u>color</u>, or location on the panel.			
24 NOV 11	ROBINSON R22 II	CEN12FA091	Fatal (1); Injury (1)
<u>Color association:</u> Examination of the airframe and flight control system components revealed no evidence of a pre-impact mechanical malfunction. Several instruments contained moisture and water. The instrument panel caution and warning light bulbs, which lenses were orange and red in <u>color</u>, were examined for filament stretch. The "Low RPM" bulb displayed minimal stretch and no stretch was noted on the other bulbs.			
15 FEB 12	BELL 407	WPR12GA106	Fatal (1); Injuries (2)
<u>Color association:</u> In the AFF system, aircraft are depicted on the screen in blue if they are active, and in red if they have lost communication, which can be due to several factors.²⁸⁶ If the system did not receive an alert, the operator would have to notice the aircraft symbol on the screen turned red. Both of the dispatchers who were monitoring the flight reported that the AFF did not change the <u>color</u> of the helicopter screen symbol until well after they knew about the accident, despite their repeated queries of the system.			
07 AUG 15	ROBINSON R44	CEN15CA348	Injuries (1)
<u>Color association:</u> The pilot was flying over the field to be sprayed looking for obstacles. Seeing none, he commenced spraying and collided with power lines. The pilot said the power lines were only 13 feet off the ground and were green in <u>color</u> blending in with the background crops. The helicopter's canopy contacted the power lines, and then the lines slid beneath the helicopter and caught the skids.			

symbol, which turns red if aircraft communication is lost, depended only on color and went undetected by tracking operators when the aircraft went down. In addition, there is the question

²⁸⁶ NASA research pilot R. Ranaudo believes the aviation community has developed good standards for red, yellow, and green, but use of other colors representing a status or condition needs further investigation. For example, the color magenta – it can be used for lots of indications. A flight management system (FMS) may use magenta for indicating the active route. But on the same aircraft, magenta also indicates lack of data. Yellow on the instrument landing system localizer (LOC) means the course localizer is armed, but not captured; it turns green when captured. White may be used to provide system status, but he believes cyan also may be used for the same purpose. A number of FAA and Department of Defense (DoD) documents recommend/require certain color applications in the cockpit. He believes audio alerting combined with color has significantly improved situational awareness.

of the performance of the operators in detecting and concluding a color change had occurred when the change was not viewed directly. In the second event (NTSB No. CEN15CA348), an agricultural pilot spraying a field collided with power lines. The pilot reported said the power lines were only 13 feet off the ground and were green in color and blended in with the background crops.

Overall, searches of the NTSB accident database did not produce any significant evidence of a substantial role of color (either inside or outside the cockpit) in aviation accidents. Even so, the searches did identify two general areas where color issues could be present in accidents and may be useful in investigating U.S. Army accidents. These are (not surprisingly) the use of color in displays and markings, and pilot CVDs. (See *New and Continuing Color Issues and Future Research* section.)

Nonetheless, it is only fair to recognize the large anecdotal evidence of military and civilian pilots with CVDs flying for decades without incident. Dr. Q. Snyder, a retired USAF flight surgeon and aeromedical adviser for the Air Line Pilots Association, International, has stated, “We have seen a number of color deficient pilots and controllers perform well, without any adverse impact on safety” (Werfelman, 2008). This position is supported by Dr. A. Pape, a former official of the Aircraft Owners and Pilots Association of Australia and aviation medical examiner. Pape (1994; Pape & Crassini, 2012), who has a color vision deficiency and holds a commercial pilot license, is the founder of the Colour Vision Defective Pilots Association (CVDPA) in Australia. He has argued color vision deficiencies were irrelevant to a pilot’s safe operation of an aircraft. “The disability of defective color perception is confined to reduced sensitivity to that property of light defined by its wavelength...Color defectives have the same capacities as color normals to perceive form, motion, depth, luminance contrast, and so on...[and] the same capacities as color normals for complex perceptual motor skills forming a part of...flying airplanes.”

For the military to adopt such a lenient philosophy, it would be necessary to: a) fully investigate and document the role of color and color vision in aviation accidents; and b) develop new guidelines to help accident investigators in identifying underlying color or color vision issues that could have played a role in accident chain of events (see Issues #7 and #8 in *New and Continuing Color Issues and Future Research* section).

U.S. Army Combat Readiness Center (USACRC)²⁸⁷ accident/incident database.

The USACRC maintains a database and assists in the investigation of U.S. Army aviation and ground accidents. This database is known as the U.S. Army Risk Management Information System (ARMIS). Accidents in the database are classified according to personnel loss/injury and property loss/damage. Over time, property loss/damage thresholds have changed; current definitions of classes are (U.S. Army Combat Readiness/Safety Center, 2017):

²⁸⁷ The U.S. Army Combat Readiness/Safety Center (USACRC) is located at Fort Rucker, Alabama.

- Class A – An Army accident in which the resulting total cost of property damage is \$2,000,000 or more; an Army aircraft or missile is destroyed, missing, or abandoned; or an injury and/or occupational illness results in a fatality or permanent total disability.
- Class B – An Army accident in which the resulting total cost of property damage is \$500,000 or more, but less than \$2,000,000; an injury and/or occupational illness results in permanent partial disability, or when 3 or more personnel are hospitalized as inpatients as the result of a single occurrence.
- Class C – An Army accident in which the resulting total cost of property damage is \$50,000 or more, but less than \$500,000; a nonfatal injury or occupational illness causing one or more days away from work or training beyond the day or shift on which it occurred or disability at any time (that does not meet the definition of Class A or B and is a lost time case
- Class D – An Army accident in which the resulting in total cost of property damage is \$2,000 or more but less than \$50,000, a nonfatal injury or illness resulting in restricted work, transfer to another job, medical treatment greater than first aid, needle stick injuries, and cuts from sharps contaminated from another person’s blood or other potentially infectious material, medical removal under medical surveillance requirements of an Occupational and Safety Health Administration (OSHA) standard, occupational hearing loss, or a work-related tuberculosis case.
- Class E – An Army accident in which the resulting total cost of property damage is less than \$2,000.
- Class F (aviation only) – Recordable incidents are confined to aircraft turbine engine damage because of unavoidable internal or external foreign object damage, and is the only damage (does not include installed aircraft auxiliary power units).

ARMIS contains accident reports from FY72 to present. In view of the much smaller ARMIS database (as compared to the NTSB), the search looked at the period of FY72 (1 OCT 71) to FY17 (31 DEC 16). As with the NTSB database search, the keyword “color” was used as the search criterion. The search returned a total of 103 accidents; however, the search keyword could not be found during the review of the accident reports for eight of the 103 investigation reports, reducing the number of accidents/incidents with narratives containing the keyword “color” to 95.²⁸⁸

Of the 95 identified U.S. Army helicopter accidents/incidents, there were two more common types of occurrences of the search term “color.” The first involved insufficient terrain color contrast for various encountered objects (e.g., loose parachutes, support posts, trees, rocks, and boxes) (9 events; 9.5%). The most interesting of these (Case 1985-05-29-005) involved the landing sequence of a fixed-wing C-12 Huron. During round-out, a crane-like bird flew up from the runway and struck the bottom of the aircraft breaking the #1 Automatic Direction Finder sense antenna. Because the bird's coloring closely resembled that of the runway, it remained undetected by the crew until it flew off the runway and struck the aircraft. Equally common was the occurrence of the search keyword associated with color contrast of power transmission wires and various cables against terrain or background (9 events; 9.5%).

²⁸⁸ It is possible that the search keyword was in redacted sections of the original investigation report.

The other color occurrences can be loosely categorized as follows (with examples):

- External to aircraft, e.g., tower light color misidentified as aircraft lighting; paint transfer resulting from collision; color of post-collision fire and smoke; green residue from tree strike
- Aircraft interior, e.g., color MFD, fire extinguisher
- Aircraft components, e.g., bearings, blades, wear residue
- Maintenance, e.g., color of tools or tool box left in engine compartments by accident; lubricant color; color bands or index marks on blades, retention plates, pitch control rods, and pitch beam; color banding on resistors on circuit boards
- Safety, e.g., student pilots are wearing locally fabricated, 2" wide nylon watchbands (similar in color to their flight class colors) which could result in thermal injury in the event of an aircraft fire; tie-down rope color made it impossible for crew chief to detect at night
- Investigator recommendations, e.g., adding color to tail rotor to increase conspicuity; change in runway lighting color; change color of ac airframe panel cover to increase conspicuity during preflight; maintenance personnel to spray paint the phenolic blocks bright color; color code various components for easy detection and recognition ; have the stud assembly turnlock painted a color in such a way as to indicate locked/unlocked position; color code high potential hazards on maps; color code fuel lines; paint tools a bright color (fluorescent yellow) to aid in identifying tools left on/in an aircraft; use of color photographs during accident investigations

As with the NTSB civilian database search results, a high percentage of the identified accidents/incidents (5 events; 5.2%) resulted in the identification of the use of color “inside” the aircraft/cockpit as a causal factor; and, only one of these was in the last 10 years (ARMIS Case 2011-12-08-012) (see Table 21). In this event, while conducting a go-around in an OH-58 D(R) during a training flight, the instructor pilot (IP) failed to estimate control input and inadvertently adjusted the throttle grip beyond the 75 degree index mark to full open. As a result, the rotor RPM rose rapidly requiring the IP to adjust the collective to control it, causing an over torqueing of the transmission and damage to the drive train. After confirming the over torque condition, the crew landed the aircraft safely without further incident. The investigation finding was the markings placed on pilot's collective were inadequate to quickly identify between normal and emergency operation, i.e., the throttle grip marking for normal operation is red while the throttle grip marking for the emergency procedure in the operator's manual is white. Additionally, the markings are made with similar dimensions using reflective gloss paint. During high glare conditions, the pilot may be unable to accurately determine which mark is being referenced solely by color. As a result, the throttle was placed in the full open position, and when the rotor RPM rose rapidly requiring the IP to adjust the collective, causing an over torque of the transmission and damage to the drive train. Review of the OH-58D(R) operator's manual and the aircrew training manual revealed there is no discussion of differentiating between the two marks on the throttle grip by color. An investigation recommendation was to redesign the OH-58D(R) throttle grip and collective head markings using both color and shape to differentiate between normal and emergency operation positions.

Table 21. Selected results of search of USACRC ARMIS aviation accident database using “color” as search keyword.

Event date	Aircraft Make/Model	ARMIS Case No.	Event severity
10 May 73	UH-1B Iroquois/Huey*	1973-05-10-007	Class B
<u>Color association:</u> On climb out after takeoff crew noted rise in engine temperature. The IP elected to return for landing. As he was turning in the pattern fire warning light came on. Aircraft was autorotated and landed hard. Landing gear collapsed. The student observer stated the fire light was on, though no actual proof of this was found. <u>Findings:</u> The possible misinterpretation of the warning lights in that the RPM LIMIT LIGHT is of the same <u>color</u> and approximate size, and is located just to the left of the fire warning light and on the same level of the panel. Design is a nonrelated factor in that both the FIRE WARNING LIGHT and LOW/HIGH RPM limit lights are of the same shape, size, and <u>color</u> and are located in close proximity to each other. Visual inspection of the engine revealed no defects. A test cell operational run of the engine revealed that the engine and its components met or exceeded all test cell requirements. The engine temperature was steady and well within limits. <u>Flight Standardization Board (FSB) remarks:</u> Less of a <u>color</u> issue, more of a communication (issue) and failure to verify the failure.			
19 NOV 81	UH-1V Iroquois/Huey*	1981-11-19-024	Class C
<u>Color association:</u> Pilot was making hoist lift when hoist fell out of aircraft, knocking the crew chief out of aircraft as it departed. The crew chief climbed back into aircraft as IP took controls and told pilot to cut the cable and maneuvered clear of debris and landed. Crew chief was taken by medevac aircraft to hospital. The IP shut down and found that entire hoist had departed aircraft ripping wiring out of cargo area and sustained major damage upon ground impact. IP and pilot were taken to hospital by ground vehicle. As an interim fix, a maintenance work order (MWO) was issued to highlight the quick disconnect lock condition and ease recognition of an unlocked condition by <u>color</u> coding the upper quick release adapter to show green when slide is in locked position and to show red when it is in an unlocked position. <u>FSB remarks:</u> Hoists are not currently <u>color</u> coded to show locked condition.			
9 JUL 82	JOV-1D ²⁸⁹ Mohawk	1982-07-09-002	Class C
<u>Color association:</u> Before landing, the check-left main landing gear indication was unsafe; the pilot recycled the gear 20 to 25 times without correcting problem. Tower personnel said gear appeared down during low pass. Pilot inadvertently jettisoned external fuel tanks while activating emergency landing gear extension pressure. <u>Findings:</u> The pilot was highly fatigued, having flown multiple missions and poor crew rest cycle. The location of the external stores release handle is within close proximity of the pilot, whereas the emergency gear extension handle is at a further distance. Both are yellow-black in <u>color</u> and are the same shape. This may have caused a period of confusion. <u>FSB remarks:</u> (The) jettison switches are <u>color</u> coded (black-yellow stripes) and guarded.			
25 JAN 83	EAH-1S Cobra*	1983-1-25-015	Class C
<u>Color association:</u> While conducting NVG qualification training, the IP demonstrated a low-level autorotation. The IP utilized maximum available collective pitch causing a low rotor condition allowing the aircraft to descend 1 to 2 feet to the runway abruptly. <u>Finding:</u> The contrast, <u>color</u>, and texture of the runway under NVGs increases the stress and fatigue load on IPs. It is difficult to acquire proper visual cues to judge the rate of closure and altitude while performing NVG nonstandard training. <u>Recommendation:</u> Unit level action – Stress the importance to the unit IPs of recognizing contrast, <u>color</u>, and texture differences and their effects on various surfaces.			

²⁸⁹ The Mohawk JOV-1D is an armed fixed-wing aircraft no longer flown by the U.S. Army.

Table 21 (continued). Selected results of search of USACRC ARMIS aviation accident database using “color” as search keyword.

Event date	Aircraft Make/Model	ARMIS Case No.	Event severity
20 FEB 86	AH-64A Apache	1986-02-20-001	Class A
<u>Color association:</u> During maintenance recovery flight, the mechanic inadvertently activated the engine chop control. <u>Finding:</u> Caution/warning marking of the engine chop control, i.e., the design of the control does not provide for identifying this control by either a caution/warning label or painting it with caution/warning <u>color</u> markings. <u>FSB remarks:</u> Chop control on collective is <u>color</u> coded, has a distinctive tactile pattern, and is safety wired (requires additional force to snap wire) to activate. FSB Pilots believe the accident likely due to lack of training and poor communication between pilot and mechanic.			
11 DEC 93	AH-1F Cobra*	1993-12-11-007	Class C
<u>Color association:</u> During NOE battle drill training maneuvers involving the multiple integrated laser engagement system (MILES), the crew allowed the main rotor blades to strike trees. The crew stated that they were flying more aggressively than usual due to the possibility of being targeted by the MILES. The crew became too involved in the combat aspect and did not pay enough attention to aircraft clearance. <u>Finding:</u> Improper design – While flying NOE, facing into the sun, the pilot was not able to use the smoke <u>color</u> visor to reduce sun glare. When the aviator’s flight helmet is fitted with the helmet sighting system (HSS) and the AN/AVS-6 night vision goggle (NVG) mount, the visor cannot be lowered over the pilot’s eyes. This lack of ability to use the visor contributed to the glare while flying into the sun and violates regulations which require eye protection during refuel operations. This special observation did not contribute to this accident; however, the accident investigation board concluded that it should be brought to the attention of the command. <u>FSB remarks:</u> No Recognized <u>color</u> issue. Pilots likely unable to see out the window due to glare and not a problem with glare on instruments or <u>color</u> related to instruments.			
19 OCT 95	OH-58DI Kiowa*	1995-10-19-001	Class B
<u>Color association:</u> During a training flight, the pilot was conducting a simulated engine failure from 1,000 feet mean sea level, when the aircraft’s rotor RPM deteriorated below normal operating RPM during the termination-with-power phase of the simulated forced landing. The IP attempted to recover the aircraft at approximately 100 feet AGL with low rotor RPM. The aircraft contacted the active runway, tail low, causing damage to the aircraft’s landing system, undercarriage, and tail boom section. <u>Finding:</u> (Present and contributing) The inability of the crew to timely identify the engine failure, combined with the autorotation characteristics. The low rotor RPM audio overrode the engine-out audio, and the green <u>color</u> throughout the entire range of the engine gas producer, power turbine, and the turbine gas temperature indicators made visual engine-out identification difficult. The green <u>color</u> throughout the range of the indicators also deviates from specifications in applicable military standards. <u>FSB remarks:</u> Aircraft was not MIL-STD compliant and engine instruments should have been <u>color</u> coded accordingly.			
17 JUN 04	C-12T3 Huron	2004-06-17-001	Class C
<u>Color association:</u> Crew experienced dual-engine inter-turbine temperature exceedance during the final phase of climb-out. <u>Findings:</u> It is our determination that the over temp condition occurred as a result of a failure to reduce power and to monitor the inter-turbine temperature gauges as the Ice Vanes were being extended. In addition, the digital gauge numbers do not change <u>color</u> when limits are approached and or exceeded. <u>FSB remarks:</u> Digital gauges should indicate limits through <u>color</u> change (yellow and red). <u>Recommendation:</u> That the Army adopt file civilian instrument standards that incorporate <u>color</u> changes to the numeral readouts as the instruments pass through the normal, cautionary, and exceedance ranges.			

Table 21 (continued). Selected results of search of USACRC ARMIS aviation accident database using “color” as search keyword.

Event date	Aircraft Make/Model	ARMIS Case No.	Event severity
1 APR 10	UH-60A Blackhawk	2010-04-01-015	Class C
<u>Color association:</u> During flight, the right-side crew chief looked aft, saw the aft cargo window was missing and the forward cargo window was partly out. Crew chief pulled forward cargo window inside aircraft. During postflight, the pilot noticed damage to tail rotor blades. <u>Finding:</u> Due to the <u>color</u>, it would be easy for aircrews to misidentify when door window jettison mechanism welds are up and locked, and when door window jettison mechanism welds are only partly locked or unlocked. It is an emergency exit and the door window jettison mechanism welds should be easy to identify whether they are up and in the locked position.			
8 DEC 11	OH-58DR Kiowa Warrior	2011-12-08-012	Class C
<u>Color association:</u> While conducting a go-around in an OH-58 D(R) during training at 212 feet AGL and 44 Knots-Indicated Air Speed (KIAS), the IP failed to estimate control input, i.e., the IP inadvertently adjusted the throttle grip beyond the 75 degree index mark to full open. As a result, the rotor RPM rose rapidly requiring the IP to adjust the collective to control it, causing an over torque of the transmission and damage to the drive train. After confirming the over torque condition, the crew landed the aircraft safely without further incident. Maintenance confirmed the over torque condition and replaced the drive train. <u>Finding:</u> The markings placed on the pilot's collective were inadequate to quickly identify between normal and emergency operation, i.e., the throttle grip marking for normal operation is red while the throttle grip marking for the Manual Operation emergency procedure in the operator's manual is white. Additionally, the markings are made with similar dimensions using reflective gloss paint. In addition, during high glare conditions, the pilot may be unable to accurately determine which mark is being referenced solely by <u>color</u>. As a result, the throttle was placed in the full open position, and when the rotor RPM rose rapidly requiring the IP to adjust the collective, this caused an over torque of the transmission and damage to the drive train. A review of the OH-58D(R) operator's manual and the aircrew training manual revealed that there is no discussion of differentiating between the two marks on the throttle grip by <u>color</u>. <u>Recommendation:</u> Redesign OH-58D(R) throttle grip and collective head markings using both <u>color</u> and shape to differentiate between normal and emergency operation positions.			

*The AH-1 Cobra attack, OH-58 Kiowa scout, and UH-1 utility helicopters are no longer part of the U.S. Army active fleet.

This event is symptomatic of what happens with poor integration in a tactical aircraft. The problem of misidentification arises especially when a pilot is performing a flight task requiring all of the pilot’s attention resources to be directed out the window. NASA research pilot R. Ranaudo (personal communication, September 15, 2017) relates an incident where he inadvertently dropped a rocket pod instead of shooting off the rocket, because the rotary switch to arm the rocket was also the one having a position on it to jettison the rocket – and, it located out of normal view behind him on the side console. Additionally, the red “pickle” button on the control stick was also the button the pilot depresses to jettison the pod. Congruency in color and shape is important to prevent misidentification, but pilots also wear gloves, and the resulting lack of tactile sensitivity has to be considered. Ranaudo also points out that with respect to color usage on controls, its effectiveness is severely decreased, if not completely when used for items not within the pilot’s normal scanning view of cockpit controls and instruments.

In another event of note (No. 1995-10-19-001), involving an OH-58DI Kiowa, the crew was unable to timely identify an engine failure. A contributing factor was the green color presented throughout the entire range of the engine gas producer, power turbine, and the turbine gas temperature indicators, which made visual engine-out identification difficult. The green color throughout the range of the indicators also deviated from specifications in applicable military standards. The final determination was the aircraft was not compliant with the applicable military standard (MIL-STD), and engine instruments should have been color coded accordingly.

In a similar event (ARMIS Case No. 2004-06-17-001), the crew of a C-12T3 Huron²⁹⁰ experienced dual-engine inter-turbine temperature exceedance during the final phase of climb-out. While investigation findings determined the over temp condition occurred as a result of a failure to reduce power and to monitor the inter-turbine temperature gauges, it also was noted the digital gauge numbers do not change color when limits are approached and or exceeded.²⁹¹ FSB remarks: Digital gauges should indicate limits through color change (yellow and red). Recommendation: The Army adopt the civilian instrument standards incorporating color changes to the numeral readouts as the instruments pass through the normal, cautionary, and exceedance ranges

The issue of color coding (or lack of) of various switches, handles, and indicator lights was identified in three other color-associated events (ARMIS Case No. 1973-05-10-007, 1981-11-19-024, and 1982-07-09-002. See Table 21 for summaries. In the 1982 accident, the pilot of a JOV-1D Mohawk responded to an unsafe landing gear indication by recycling the gear 20 to 25 times without success. While activating emergency landing gear extension pressure, the pilot inadvertently jettisoned the external fuel tanks. The investigation finding was the pilot was highly fatigued, having flown multiple missions and poor crew rest cycle. The location of the external stores release handle is within close proximity of the pilot, whereas the emergency gear extension handle is at a further distance. But both were yellow-black in color and had the same shape. This may have caused a period of confusion.

Table 21 also includes three events that while not integral to the aircraft cockpit are related to human interaction with color. As an example (ARMIS Case No. 1983-1-25-015), while conducting NVG qualification training, the EAH-1S Cobra IP was demonstrating a low-level autorotation. The IP utilized maximum available collective pitch causing a low rotor condition allowing the aircraft to descend 1 to 2 feet to the runway abruptly. The investigation finding was the contrast, color, and texture of the runway under NVGs increased the stress and fatigue load on the IP. It is difficult to acquire proper visual cues to judge the rate of closure and altitude while performing NVG nonstandard training.

None of the accidents in the ARMIS database narratives mentioned the presence of CVDs. However, a study conducted by Bailey (1972), having access to pilot medical records, was one of very few studies that have investigated the role that the presence CVDs played in early U.S. Army aviation accidents. Fourteen pilots were randomly selected from the population

²⁹⁰ The Mohawk JOV-1D is an armed fixed-wing aircraft no longer flown by the U.S. Army.

²⁹¹ R. Ranaudo states when he was flying the NASA Bombardier CRJ-900 research aircraft, if there was an interstage turbine temperature (ITT) exceedance, the gauges turned red and began flashing. An aural message of the overheating also was sounded. From personal experience, he believes color should be used to denote urgency, but color alone does not always capture attention (personal communication, September 15, 2017).

of pilots known to have color deficiencies. A detailed analysis by colorimeter identified them as anomalous (mild to moderate) or protanomalous or deuteranomalous type. A matching sample of 14 pilots was then selected from a pilot population with normal color vision and matched with respect to age and total flight time. The accident record for each individual was examined to determine whether anomalous color vision in U.S. Army pilots could be identified as a significant factor to flight safety.

The accident data used were provided by the United States Army Board for Aviation Accident Research (USABAAR),²⁹² Fort Rucker, AL. Their classification scheme was:

- a. Major -those accidents which result in total aircraft loss or cause substantial damage to major systems.
- b. Minor -those accidents or incidents which result in a lesser amount of damage than those classified as major.

Statistical tests were one tailed with a confidence level of 0.90. These tests yielded statistical significance between groups for major accidents but not between groups for total and minor accidents. Thus, the null hypothesis stating that there was no difference between color defectives and normals was rejected only in the case of major accidents. For in this category, color normals had more accidents than color defectives.

The study concluded from a statistical as well as from a practical viewpoint that mild anomalous trichromats do as well and, it would appear, in some cases better than color normals in terms of aircraft accidents. However, it was noted that no consideration was given to forced landings and precautionary landings.

A literature search identified only one other study that specifically looked at the accidents and pilots with known CVDs. This study was conducted by the FAA Civil Aeromedical Institute, Oklahoma City, OK, looking at civilian accidents in 1976 with respect to eight physical defects of pilots, one of which was flying with deficient color vision but with a SODA waiver, i.e., passed a signal gun test and had no operational limitation (Dille & Booze, 1979). It was found that the observed-to-expected accident ratio was 1.91 for the defect of color deficiency, indicating a higher accident rate. In a review of individual accident records no effect was found between the visual defect of the pilot and the accident cause, phase of flight, type of flying, time of day, or weather conditions.

Interestingly, almost a decade earlier in 1965, COL R. Bailey, Commander, U.S. Army Aeromedical Research Unit (USAARU), Fort Rucker, AL, and author of the above study, in an internal report on color vision standards and testing, suggested that it would be of interest to the U.S. Army to conduct such a study to compare accident and mission accomplishment rates for aviators flying with waivers for known color deficiencies and a match sample of color-normal aviators. Remarkably, 46 years later, in 2011, Pape & Crassini, writing for the Journal of the Australasian Society of Aerospace Medicine, make the same argument:

²⁹² The U.S. Army Board for Aviation Accident Research (USABAAR) was established in 1957. In 1972, it was redesignated as the U.S. Army Agency for Aviation Safety, then in 1978 as the U.S. Army Safety Center (USASC). In January 2005, the USASC became the U.S. Army Combat Readiness Center (USACRC).

Since [the development of current standards], there has emerged a cohort of pilots with defective colour perception yet with extensive experience flying modern, large, and sophisticated aircraft. We argued that these pilots represent a potential pool of participants for a definitive test of the aviation colour vision standard. We proposed that such a definitive test should involve comparison of the "performance of duties" (to quote the International Civil Aviation Organisation [ICAO] colour standard) on an appropriate set of flight simulator tasks of two groups of pilots matched on all relevant variables, and differing on the variable of colour perception abilities. We appreciate that carrying out the evaluation we propose would be a complex and expensive undertaking. However, we feel that the effort is warranted because the results of the kind of evaluation we propose would provide the strongest possible basis for the need for and continued application of the colour perception standard, or its removal.

So, it appears that large-scale studies still need to be conducted to fully understand the role of color in aviation accidents (see Issue #7 in *New and Continuing Color Issues and Future Research* section).

Pilot error, displays, and color.

In summary, the above searches of accident databases maintained by both the NTSB and the U.S. Army failed to provide sufficient evidence of color as playing a significant role in aviation accidents. However, in both of these databases, pilot error is often cited as the major causal factor in accidents. In an analysis of the accidents in the NTSB database involving U.S.-registered civil helicopters from 2001 through 2010, 69% of accidents were attributed to pilot error (Rash, 2012). This implies that approximately seven of every 10 accidents were a consequence of human action – or lack of action – by pilots. In the searches performed for this paper, pilot error was a common investigation finding, being characterized as the pilot having "failed to maintain altitude," "failed to maintain airspeed," or "failed to maintain aircraft control."

It is a characteristic of humans (pilots) to make mistakes. If these mistakes lead to accidents, it is important to understand the nature of these mistakes. Pilot error almost always has underlying causes, which are often the real reason for an accident. These causes can include high (or low) workload, fatigue, stress (personal and professional), poor situational awareness, inadequate training, lack of crew coordination, and poor ergonomic design. One or all of these causes can degrade performance, leading to accidents.

One formal definition of human (pilot) error is "an inappropriate action or intention to act, given a goal and the context in which one is trying to reach that goal" (Felciano, 1995). Human error can include any of the following (Adams, 2016):

- Failing to perform, or omitting, a task;
- Performing a task incorrectly;
- Performing an extra or non-required task;
- Failing to perform a task within the required time limit; and,

- Failing to respond adequately to an emergency situation (which abruptly changes not only the goal but also the tasks required to achieve the new goal).

Color in any environment, which includes the cockpit, can affect human (pilot) actions and reactions (Colormatters.com, 2017). But, it is unknown how and to what extent color as a feature of display and indicator features may play a role in failures in decision making. Color can create conditions that can cause fatigue, increase stress, decrease visual perception, increase human errors, and negatively affect orientation and safety (Kopala, 1979; Hollands & Merikle, 1987; Bemis, Leeds, & Winer, 1988; Beringer, Allen, Kozak, & Young, 1993; Francis & Reardon, 1997). HFE research over the past decades have clearly demonstrated that both display hardware and information formatting features impact pilot performance and error rates, resulting in a number of design guidelines (Mejdal, McCauley, & Beringer, 2001) (see *Guidelines for Use of Color in Cockpit Displays* section). Integral to these guidelines has been the display feature of color (Christ, 1975; Krebs, Wolf, & Sandvig, 1978; Boff & Lincoln, 1988a,b; SAE, 1988). While the automation of the cockpit often is linked to a decrease in accidents, a large number of incidents have been associated with and caused by the interaction between this automation and the human (pilot) (Billings, 1997). Many of the issues raised concerning automation (especially color) in the cockpit apply to the presentation of information on MFDs. For this, and other reasons, aviation experts continue to call for the consideration of the color dimension in all accident/incident investigations and reviews, to include specialized databases that focus on color vision related accidents/incidents (Menu et al., 2001).

In accident investigations, human failures are the most difficult to analyze. Laboratory tests of fuel, lubricants, and component wear and failure have become highly sophisticated and universally available. A complicating issue is that no accident is caused by a single hazard or factor. HF are found in the majority of all accidents. They influence pilot and crew decision-making abilities and performance to play a major role in causing accidents or contributing to the chain of events that result in an accident. In accident investigation practices, the awareness of the role of color vision and its interaction with color design and schemes in the cockpit (and crew areas) has not been studied and established as well as material failure. With the improvement in design, manufacturing, and quality control of aircraft and systems continue to improve, human (pilot) error will become more and more dominant as the major casual factor in accidents. The aviation safety community must assist investigators in teasing out and understanding the finer points of human performance. One of these points is the use of color and its interaction with color vision. Color experts could assist in the development of accident investigation guidelines capable of capturing the role of color and color vision performance in accidents (see Issue #7 in *New and Continuing Color Issues and Future Research* section).

New and Continuing Color Issues and Future Research

After exhaustively exploring color from the many various approaches and thereby achieving the first goal of this white paper (i.e., addressing the knowledge gaps that exist between the various factions involved in the planning, design, manufacture, and implementation of color in U.S. Army cockpits), a limited number of issues identified as potential areas of investigation for the purpose of improving the effectiveness of color usage on performance and safety in U.S. Army cockpits are presented. The format is to identify the issue, provide sufficient

background material and discussion to place the issue in perspective, and make recommendations for addressing the issue. This section closes with a suggested area of future research using machine learning methods based on learning data representations (e.g., AI and deep learning) that simulate the neocortex's large array of neurons in an artificial neural network (Hof, n.d.). While decades old, improvements in mathematical formulas and increasingly powerful computers are revolutionizing this approach to problem-solving, an approach having tremendous potential for the use of color displays in the U.S. Army cockpit.

Issues.

Issue #1: Use of COTS color displays vs. Government-mandated design requirements – If, as it has, the U.S. Army moves to COTS displays, then control over color as well as consistency across airframes may be compromised.

Discussion: Military avionics have a number of special requirements due to the dynamic and demanding operating environments of aviation as well as the need for high reliability. In decades past, these requirements were not met by COTS components and systems, requiring long-term and expensive developmental programs. Driven by today's cost-conscious culture and aided by the explosion of technology advances in speed, size, weight, and reliability, civilian aviation avionics manufacturers now provide avionics meeting military requirements in most, but not all, areas.

However, the integration of the first COTS AMLCDs into the military cockpit faced some initial issues (Livada, 2012). COTS AMLCDs had to be adapted for military use via specialized modifications in mechanical, electronic, and software (firmware) design with some compromises required (Tannas, 1994; Hopper, 2000; Livada, 2012). An issue that may be well overlooked is control over color schemes, as well as consistency in color across airframes, which may compromise pilot training and performance. With the possibility of a mixture of displays, there will be great difficulty in knowing which display designs and/or color schemes are the most effective.

Recommendation: a) Develop a database documenting color schemes for currently fielded and considered COTS displays and considered b) Evaluate Investigate how deep learning techniques may be used to evaluate pilot performance for specific color schemes as well as scheme consistency across displays and aircraft (see *Future research* section).

Issue #2: The impact of operational conditions on the visual performance of aviators with CVDs – The aviation community is aware of the possible, however transient, impact operational conditions in aviation can have on color vision performance. However, most studies have focused on effects of these factors on color normals, not on aviators with impaired color vision, i.e., with CVDs.

Discussion: Numerous studies have demonstrated individuals with CVDs perform less well than color normals in tasks that require color discrimination or identification (Gaska, Wright, Winterbottom, & Hadley, 2016). The list of operational and environmental factors capable of degrading color vision performance, even transiently, is quite broad. These include dynamic and

extreme lighting environments, high-G (MacGillis, 1999), vibration, hypoxia, background effects, age, chromatic adaptation, employed display color schemes, and a host of others. Many, but not all of these, have been investigated in various degrees for color normal, but not for individuals with known CVDs.

Of the operational factors impacting color vision and aviation safety overall is hypoxia (Vingrys & Garner, 1987; Barbur & Connolly, 2011; Temme, St. Onge, O'Brien, 2017). The risk of hypoxia in aviation is the result of the decrease in the density of air with altitude. The USN considers cockpit hypoxia to be the number one safety issue for Naval aviation (Cable, 2003; Deussing, Artino, & Folga, 2012; Seck, 2016). While helicopter operations typically are not conducted at altitudes customarily associated with hypoxia (i.e., > 10,000 ft above mean sea level), surveys of rotary-wing aircrew flying in unpressurized cabins at altitudes of <10,000 ft have reported a high frequency of symptoms commonly attributed to hypoxia, e.g., difficulty with calculations, feeling light-headed, delayed reaction time, and mental confusion (Smith, 2005). In a study of measuring oxygen saturation in UH-60J aircrews in Japan, levels were found to decrease at altitudes as low as 5,000 ft (Nishi, 2001). The overall implication being Army aircrew may be at risk for hypoxic effects at previously thought to be safe altitudes.

While military pilots have less CVDs than the general population, many of these do fly with known CVDs. A higher percentage of non-rated aircrew may consistently fly with CVDs. A limited number of studies have looked at both populations in the presence of hypoxia. One study did compare subjects with normal color vision and with a red-green CVD at ground and 12,400 ft (Hovis, Milburn, & Nesthus, 2012). The CAD color vision test showed a small (~10%) increase in the red-green thresholds for the color normals and a similar increase in the blue-yellow thresholds for subjects with the red-green CVD.

Recommendation: Investigate the impact of operational and environmental factors on color defective aircrew, especially for those factors (e.g., altitude), for which color vision is known to be compromised.

Issue #3: Duty-related color vision requirements – Today's military color vision standards do not adequately address specific duty-related color vision requirements. There are little data that shows the real, practical implications of CVDs on aviation safety. Ideally, only applicants with normal color vision as measured by the most discriminating tests would be selected. However, this policy could deny licenses to a significant number of individuals who might be able to function safely in the aviation environment. The question is where to draw the line (International Civil Aviation Organization, 2012).

Discussion: Current U.S. Army color vision requirements are generally unilaterally applied to all specialties instead of being tailored to individual occupational (or duty-related) tasks. It is reasonable to expect certain jobs would require strict color vision requirements and others could be performed by individuals with mild CVDs. This is not an uncommon issue in occupational medicine (Dain, 2004), where claims frequently are made that clinical tests bear no resemblance and no relevance to real occupational color decisions. However, while not universal, much of the color science is against such practical tests (International Commission on Illumination, 2001). Dain (2004) states practical tests can be inconsistent if carried out in different locations and in

different conditions. Thus, the alleged unfairness and irrelevancy of the test is just replaced by the difference between testing conditions.

This very issue was raised within the Army in 1974 when the Director of Personnel Management Development, Department of the Army, proposed then current color vision standards be reviewed for the various MOSs with regard to specific duty tasks. The rationale of the proposal was: 1) 90% of males and 99.5% of females in the general population have normal color vision (a verified statement), and 2) a significant portion of soldiers in service lacking normal color vision have demonstrated the ability to perform their duties (an unverified statement). Therefore, if each MOS could be evaluated for necessary color vision requirements, then standards could be reduced for many MOSs. This proposal eventually was directed to USAARL, Fort Rucker, AL. Commander, USAARL, responded by agreeing with the basic premise of the proposal. However, in 1974, there were 342 occupational specialties (MOSs). The Commander stated each of these jobs would require the development of a detailed list of visual tasks, the identification and grading of the role of color vision in each of these tasks, and finally an analysis of these data for each MOS in order to make a valid recommendation. In his opinion color vision standards could not be changed until a detailed review be accomplished.

Recommendation: The aviation community (military and civilian) frequently has called for color vision standards to become evidence-based. Such new standards should meet the full spectrum of demands required by aviation operations and reflect advances in medical capabilities for color vision evaluation. Today, U.S. the Army has approximately 190 enlisted MOSs. Time and manpower limitations would be substantial in order to evaluate color vision requirements for each MOS. However, if faced with declining enlistment rates, a limited analysis of the highest populated or most critical MOSs could be performed.

Issue #4: Lack of single, rapid color vision test – No current test is capable of screening for all types and severities of CVDs. This implies more than one test may be required, increasing time and manpower resources. Most current color vision tests are designed for administration in clinical and require specialized lighting. The availability of a field-qualified test device would be advantageous in quantifying acquired CVDs in the field, e.g., directed energy exposures.

Discussion: The myriad of tests and standards have posed a quagmire for color vision testing community for decades. While much effort has been put into analyzing specific tests and occasionally direct comparisons of two tests, there does not appear to have been a consolidated effort to evaluate all available tests in a head-to-head comparison, to include strengths and weaknesses in relation to military operational needs.

Recommendation: The first step in addressing this issue could be the application of a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis of the methodology and validity of the many color vision testing. Such an analysis would provide the ability to assess the pros and cons of each test. A limited approach to this analysis has been demonstrated in a study by Rogosic et al. (2012). Their study investigated the many differences among testing color vision tests and standards across a number of countries having color vision requirements for maritime, air, rail, and road traffic operations.

Issue #5: Effect of display color gamut on workload reduction for aircrew tasks – In early aviation display research studies, the suitability, efficacy, and benefits of color displays to the tasks performed by aircrew members have been demonstrated. However, there is not a comprehensive current corpus of knowledge associated with color gamut and cockpit flight tasks.

Background and discussion: In more recent studies, effort has been put forward towards the establishment of minimum values for luminance and color contrast required to optimize the use of colored symbols in displays (Martinsen et al., 2002; Harding & Rash, 2017). However, there exists no definitive study examining the specific display chrominance capacity's effect on the aircrew member's workload (Draper, 2017). The insertion of head mounted color displays into the military cockpit has been slow due to the cost of these displays and the lack of a clear guiding requirement on how much color gamut is enough to achieve a measurable improvement in workload reduction.

The proposed innovation then is a quantitative model of workload improvement prediction as a function of the color coordinates of the color space vertices for a color display. Interest in bringing color displays for see through applications has been growing beyond the Army and well into the Air Force and Navy. A simple solution to optimizing the color gamut for a given application is simply to provide a color gamut that far exceeds the needed gamut to ensure the gamut that is needed is addressable.

Recommendation: Conduct the necessary studies to establish the correlation of aircrew workload on the Bedford workload scale (or similar metric) as a function of addressable color space (gamut) of a color display. The correlation function determined could be published as a tool in establishing cockpit display minimum color gamut requirements with respect to specified aircrew workload as well as a predictive tool to be used in "what-if" scenarios for aircrew performance enhancement to guide further technology development to the improvement of color display color space characteristics.

Issue #6: Luminance requirements for color symbology – When color is implemented in HMDs that are eyes-out, see-through displays, visual perception issues become an increased concern. A major confound with HMDs is their inherent see-through (transparent) property. The result is color in the displayed image that combines with color from the outside (or in-cockpit) world, producing an image with additive color.

Background and discussion: For symbology to be viewed in a see-through HMD, the luminance of the symbology must be adequate to distinguish it from the see-through background. This is true whether or not symbology is displayed on a monochromatic or full-color display. When the contrast of the transparent symbology is sufficiently high, the symbology appears as an overlay on the ambient scene. For an HMD to be usable in an operational environment, the luminance requirements must take into consideration the type of displayed imagery (e.g., symbology, situational maps, target sights), the tasks (e.g., targeting, navigation, obstacle avoidance), the operational setting (e.g., day/night, terrain features), additional hardware (e.g., visors, windscreens, laser protection), and other considerations. For a color HMD, symbology color overlaid on an ambient scene must consider luminance and color contrast, which requires information about the spectral content of the landscape or ambient scene. However, optical

designers must consider all terrain features when designing a see-through optic as the military can be deployed to any geographical location around the world; this may simplify the development of luminance requirements for see-through, full-color HMDs. The reason this will simplify the development of a contrast requirement is luminance contrast, and not color contrast, is the determining factor (Harding & Rash, 2017).

In an early study to investigate luminance requirements for daylight symbology, Harding, Martin, and Rash (2005) processed simulated images of white symbology (simulating a full-color HMD with all three primary colors displayed) overlaid on a uniform field and selected static natural backgrounds of varying complexities (Figure 193). Observers evaluated the quality of symbology overlaid on the backgrounds for 200 images, 20 images per background image. Average contrasts were calculated for each of the 200 images. Based on evaluations, a recommended peak luminance of 5,470 fL was derived.

In this and subsequent studies (Harding, Rash, Lattimore, Statz, & Martin, 2016; Harding & Rash, 2017), the necessary HMD luminance to achieve good contrast was found to be a function of the complexity of the background image. This finding is in general agreement with other studies of transparent text against complex backgrounds (Hill & Scharf, 1999; Scharff, Hill, & Ahumada, 2000; Scharff & Ahumada, 2002).

The 5,470 fL peak luminance value calculated for white symbology against selected backgrounds did not take into account transmission characteristics of military hardware, e.g., visors, windscreens, and HMD combiners. Only white symbology was evaluated, as it represented the highest achievable luminance contrast.

Although the natural background images were deemed representative, the imagery was static and not dynamic. During actual flight, flight symbology would appear overlaid over a changing ambient scene. Motion tends to blur or reduce the local variations in an ambient scene (especially in NOE flight) and the background relative to the symbology has a temporal modulation component. At minimal contrast, symbology characters would likely appear recognizable in one instance and perhaps partially disappear in the next instance as the complexity and luminance flow of the ambient image waxed and waned. There is certainly a dynamic feature to the visibility and quality of symbology, and taking motion into account would likely yield more accurate results than simply evaluating static symbology.

Recommendation: A question remains of how robust is the luminance requirement determined in the study described above. The imagery observers evaluated was well-controlled, with a calibrated monitor and luminances calculated based on photometric assessments. The imagery was static, and dynamic imagery may reduce the luminance requirement but will not likely increase it. What may increase the luminance requirement is displaying imagery other than symbology (e.g., sensor imagery, synthetic imagery, tactical maps). Aviators are very familiar with the symbology set used in their aircraft. They know the function and position of each element, and this knowledge assists them in reading the symbology when contrast conditions may be poor. On the other hand, other imagery has an unknown quality about it and to correctly decipher information content requires good contrast conditions. Further studies may be needed to fully characterize the luminance requirements for full-color HMDs.

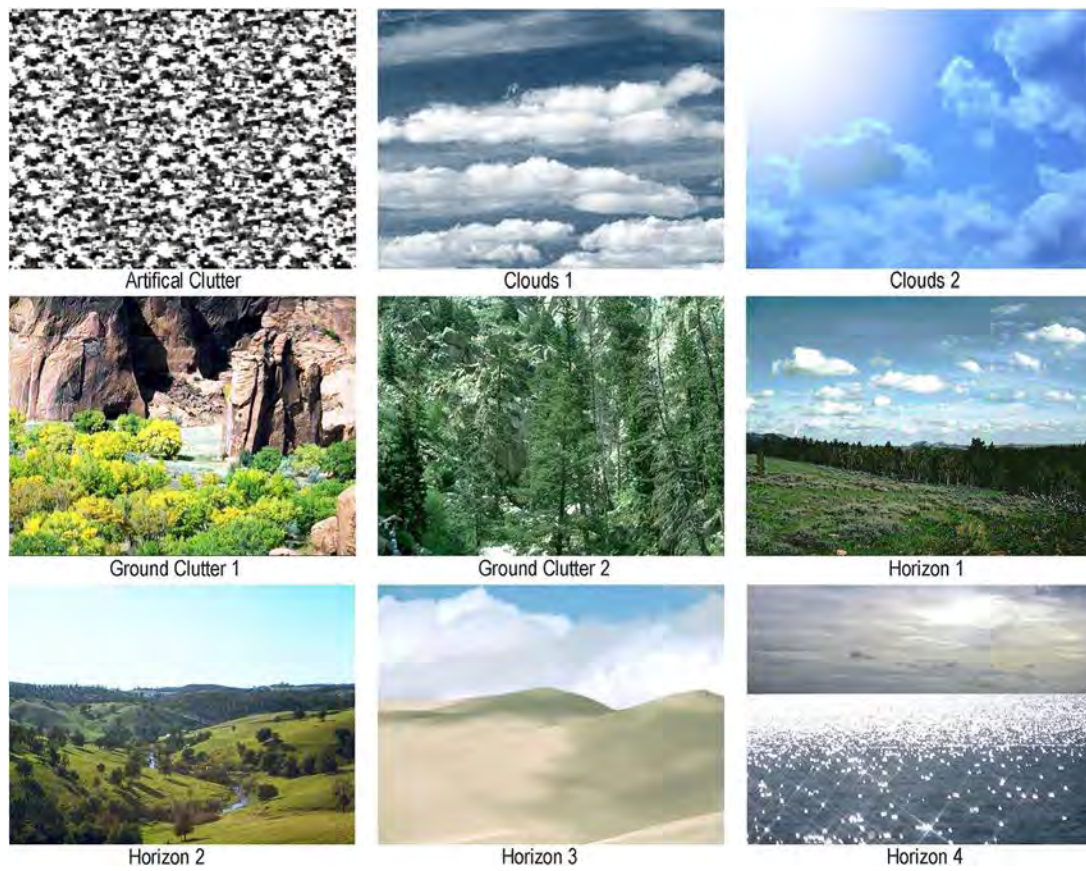


Figure 193. Images of natural backgrounds used to evaluate the quality of overlaid symbology.

ISSUE #7: Lack of full understanding of the possible role of color and color vision in aviation accidents – This lack of awareness may So, it appears that large-scale studies still need to be conducted to fully understand the role of color in aviation accidents.

Background and discussion: The incidence of color vision and the role of the use of external color in aviation accidents is best exemplified by the now famous 2002 FedEx Flight 1478 accident in Tallahassee, Florida. The aircraft crashed on final approach at night well short of the runway and the NTSB final report stated “the probable cause of the accident was the failure of the captain and first officer to establish and maintain a proper glide path during the night visual approach to landing. Contributing to the accident was a combination of the captain's and first officer's fatigue and failure to adhere to company flight procedures, the captain's and flight engineer's failure to monitor the approach, and the first officer's color vision deficiency” (National Transportation and Safety Board [NTSB], 2004). The NTSB accident database documents several other accidents where colored lighting external to the aircraft (e.g., runway, taxiway, and signal) was a factor.

However, there is a much lower frequency of occurrences where the use of color in the cockpit and its interaction with aircrew color vision are identified as causal factors. It is suggested this lower rate of incidents may be the failure of investigators to have sufficient

knowledge of color vision and its illusionary perceptual effects, as well as a knowledge of poor HFE color designs.

Recommendation: A panel of subject matter experts across all color science disciplines should be enrolled in a consolidated effort to identify potential visual perception errors associated with the use of color in displays and other cockpit/cabin applications in the aviation operational environment. With this constructed database, a set of guidelines could be developed for accident investigators to assist in ensuring any potential color-related factor is not overlooked during investigations, especially where human effort is assigned as the primary causal factor.

Further Research.

The potential for deep learning algorithms to enhance color display information and design

AI is considered to be a form of reinforcement learning in which a problem-solving computer algorithm is adjusted incrementally until processed input data exemplars consistently produce a desired output response within specified error tolerance limits. Results acquired with a training set of input data always must be validated with one or more independent test sets of data before the algorithm is deemed acceptable for use. The training input data often use information obtained from historical databases, which must be screened for erroneous and contradictory exemplars; otherwise, the training progress will be stalled.

Input data for AI training may come from a variety of sources including machine-based sensors that mimic some aspect of human sensory perception such as vision, hearing, and touch. Raw data are usually transformed or decomposed into simpler and more useful elements. For example, a full-color natural image may be reduced by image processing techniques into color and luminance channels, and subsequently each channel in turn can be simplified further into spatial elements of various frequencies and orientations representing edges or other features. Other heuristic approaches to data reduction are possible and may even be more efficient, depending on the problem being addressed. AI-based methods to assess existing color typically use RGB color space, but adjusting color displays for improved legibility is better served by separating luminance from hue. Therefore, color spaces such as CIE $L^*a^*b^*$ space as well as HSL, HSB, or HSV definitions may be more appropriate for optimizing human performance with color displays than either RGB or CMYK color spaces. However, applying color space transformations can be costly in terms of processing speed, so it is important to consider all color space constraints and requirements before beginning AI development.

Often during the early stages of AI development, there are insufficient exemplars of historical data available for training an AI algorithm. In such instances, simulated data has been used in initial stages, followed by additional final training and testing with real data (or simulations).

Once input elements are defined and extracted, the actual AI training involves the application of logic and reasoning to form a decision-making inference about the input data and how it relates to, or is associated with, a desired output response. For example, an artificially

intelligent system could be as simple as a series of “If-Then-Else” rules used to trigger a specific, pre-defined output response among multiple choices using a winner-take-all approach. Further elaboration of such an “Expert System” could include the use of probability or likelihood determinations based on historical statistics, or the use of mathematical operators to transform the signal passing through a particular stage of the decision-making process. Even more elaborate AI approaches may utilize filtering algorithms to isolate highly relevant parts of a signal from the total raw signal, such as the use of Fourier analysis, wavelet analysis, or particle detectors. For example, the detection of a visual feature element such as a red symbol from a captured video image of a cockpit display might be initiated with relatively simple segmentation filters that isolate a region of interest (ROI) specified by a range of reddish hues from the background color palette. Once the ROI is defined and located, the actual decision-making process associating the red symbol with a specific meaning requires an artificially intelligent algorithm that may incorporate several elements including color, form, position, and potentially even character-interpretation abilities to categorize the output response as a detected unique symbol with a high likelihood value.

Artificial neural networks (ANNs).

While there are many types of AI, one of the most successful forms has been the artificial neural network (ANN). An ANN is a computer model of interconnected nodes allowing information entering the network to be distributed and summed among the interconnected nodes, thereby creating an abstract form of stored memory or knowledge based on an additive information process. This process emulates a biological neural network in which living neurons are interconnected by synapses sharing additive excitatory or inhibitory signals by means of chemical neurotransmitters. Within an ANN, information flows from a well-defined input layer of feature information elements, through one or more interconnected layers of nodes (i.e., hidden layers), and exits the network through an output layer that provides a decision result.

ANNs are usually trained systematically through repeated exposures to many examples of input information to be learned, which in turn determines the weighting response to the relative importance of the information as it is shared at each interconnection (Rumelhart, Hinton, & Williams, 1986). A common approach to training is the backpropagation method that systematically adjusts the weight matrix while tracking output errors.

Color-based applications of neural networks.

There are numerous examples of ANNs having used color information as inputs for decision-making algorithms. In the field of dermatology, melanoma screening has been accomplished by assessing form, shape, and color of skin lesions (Limbaugh, Moss, & Stoecker, 1991, 1992; Cascinelli et al., 1992; Dhawan & Sicsu, 1992; Tomatis et al., 2003; Teare, Fishman, Benzaquen, Toledano, & Einekave, 2017). In ophthalmology and optometry, color has been used to screen fundus photographs for various types and severities of retinal disease (Goldbaum, Katz, Nelson, & Haff, 1990; Smolek et al., 2008; Maji, Santara, Ghosh, Sheet, & Mitra, 2015; Burlina et al., 2017; Burlina, Pacheco, Joshi, Freund, & Bressler, 2017; Gargeya & Leng, 2017; Takahashi, Tampo, Arai, Inounoue, & Kawashima, 2017; Xu, Feng, & Mi, 2017). In addition, neural networks have been used to improve the sensitivity and specificity of screening

CVDs by correlating the Farnsworth-Munsell 100 Hue test results to the more sensitive color anomaloscope data (Smolek & Hovis, 2007). In the food and beverage industry, neural networks have used color input data to assess freshness, ripeness, and the overall quality of raw and processed consumer products (Tan, Morgan, Ludas, Forrest, & Gerrard, 2000; Sofu & Ekinci, 2007; Zhang & Zhang, 2011; Fadilah, Mohamad-Saleh, Abdul Halim, Ibrahim, Syed Ali, 2012; Shafiee, Minaei, Moghaddam-Charkari, & Barzegar, 2014; Gonzalez Viejo, Fuentes, Li, Collmann, Conde, & Torrico, 2016; Liu et al., 2016; Sanaeifar, Bakhsipour, & De la Guardia, 2016). In the realm of image analysis, neural networks have been used to automatically separate foreground regions of interest from background imagery based on color information (Wu & Huang, 2002; Maddelena & Petrosino, 2008; Gemignani & Rozza, 2016). The accurate segmentation of a region of interest using an ANN approach is critically dependent both on color and on luminance, particularly for uncontrolled lighting in natural scenes (Campbell, Thomas, & Troscianko, 1997; Cardel, Funt, & Barnard, 2002; Dong & Xie, 2005). Finally, neural networks have been used to improve our scientific knowledge of color constancy perception under varying illumination conditions (Moore, Allman, & Goodman, 1991; Vladusich & Broerse, 2002; Hansen & Gegenfurtner, 2009; Seow & Asari, 2009).

Deep learning neural networks.

In the past, training neural networks on highly complex data inputs such as raw pixel data contained in images was practical only with supercomputers. In recent years, the availability of faster and cheaper computer processors and memory have made it possible to create highly complex ANNs on low-cost personal computer systems. Furthermore, parallel improvements in graphic processor units (GPUs) and software to control GPUs has largely taken the burden of performing neural network training off of the main computer CPU and placed it on GPUs that are better suited for this task. The use of GPUs for AI development has greatly simplified the analysis of raw data image files by eliminating the need for extensive manipulation and pre-processing of the input data.

These high-capacity ANNs are now referred to as “Deep Learning” in reference to their ability to break down highly complex signals into basic feature elements, and process these elements by utilizing large networks with many hidden layers. Essentially, a deep learning neural network (DLNN) is considered a more complex form of the typical ANN with a single layer of hidden neurons because it can incorporate the sensory encoding algorithm knowledge needed to decompose a raw signal together with the learned knowledge matrix of how to interpret the signal (i.e., to classify or numerically grade it).

DLNNs often take the form of convolutional neural networks (CNNs) whenever mathematically-based convolution image processing is used (Hinton & Salakhutdinov, 2006; LeCun, Bengio, & Hinton, 2015; Schmidhuber, 2015). The convolutional neural network is a special class of DLNN based on a series of overlapping image filtering kernels that deconstruct a complex raw image into a series of fundamental components (LeCun, Kavukcuoglu, & Farabet, 2010; Krizhevsky, Sutskever, & Hinton, 2012; Jia et al., 2014).

CNNs have shown great promise in medicine, including where color is a major feature of concern (e.g., the screening of retinal disease biomarkers) (Smolek et al., 2008; Burlina et al.,

2017; Gargeya & Leng, 2017; Takahashi, Tampo, Arai, Inounoue, & Kawashima, 2017; Xu, Feng, & Mi, 2017).

A different approach to DLNNs is the use of a recursive neural network (RNN), which can use computer vision methods to parse a complex image for specific instances of well-defined elements in a scene, such as a designed color scheme and format of a HMD where symbols are viewed against FLIR or I² imagery.

Deep learning for color graphic displays.

There are many potential areas of research where deep learning methods might result in improvements of color graphics displays in glass cockpits, HMDs with color symbology, and manned-unmanned teaming (MUM-T) color graphic displays. For example, MUM-T operators control semi-autonomous unmanned vehicles by interacting with a color-based graphic display that combines sensor-based symbology with camera imagery from the vehicle. The color and luminance contrast of symbology overlays must be compatible with the background imagery. Research questions include: Can DLNNs be used to predict how environmental lighting conditions and background colors adversely affect the appearance and usability of the MUM-T display? Can DLNNs anticipate human operator demands and make adjustments to the display to facilitate better operator performance? Will DLNNs help to more accurately define the minimum color vision requirements of a MUM-T operator?

Since identifying symbology in natural scenery is a current thrust of deep learning research with autonomous technology, the study of color symbology and luminance issues with semi-autonomous MUM-T operations fits well with this paradigm. One approach to begin addressing these human operator issues might be to train a DLNN to recognize various forms of color symbology (i.e., color-based optical character recognition) overlaid onto various forms of background sensor imagery as shown by the conceptual flow chart in Figure 194. It is a well-known complication that as symbology colors are varied against a colored background, some color combinations lack sufficient contrast and are difficult for human operators to visualize and identify (Harding et al., 2017). In addition, certain color combinations are expected to be similarly difficult for machine-based vision systems to interpret correctly because of the loss of contrast. This would be particularly true if the color sensitivity of the sensor system final output is designed to emulate the spectral sensitivity of human vision. Thus, it is potentially feasible to train a DLNN to model the color vision performance decrements human MUM-T operators would be expected to experience in terms of symbology identification. By developing such a model, a DLNN-based color symbology vision standard would be created by which the performance of human operators can be compared, tested, or predicted.

Training a color vision DLNN to emulate human operators should be fairly straightforward because the background imagery can be selected randomly from pre-existing databases, while the symbology itself can be generated randomly and become self-labeled inputs. Thus, a large number of simulated training input exemplars can be produced rather quickly without the need for creating and storing every possible image combination. With various stages of training of the DLNN, symbology identification errors for specific color combinations and luminance levels can be tabulated for error analysis and further study.

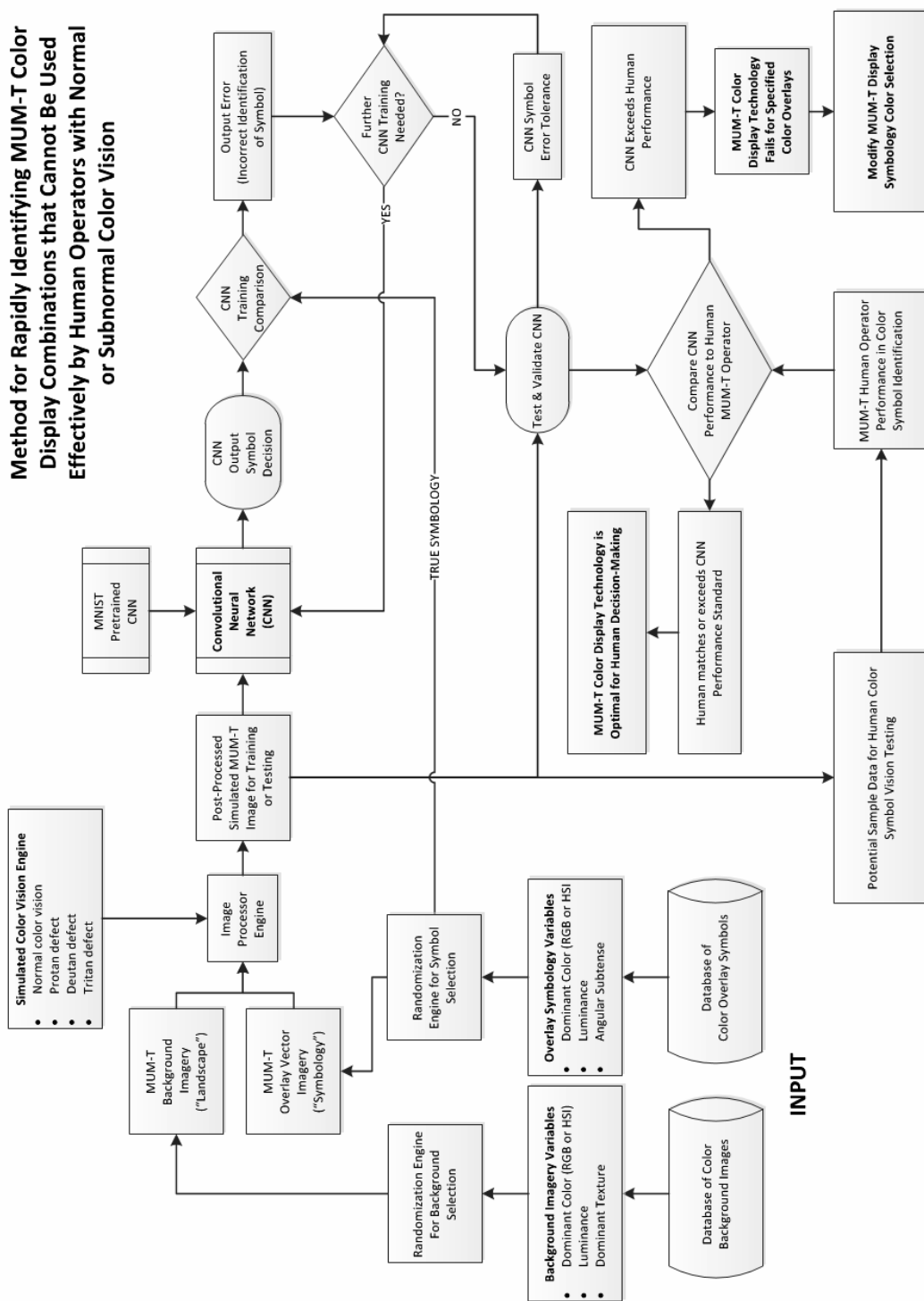


Figure 194. Conceptual flow chart for training and testing a Deep Learning Neural Network (DLNN) to study and correct color symbology identification problems with MUM-T color displays.

This basic DLNN model for MUM-T color identification can be extended further by incorporating image processing code simulating known CVDs in human operators. These exemplars of defective color vision can be passed through the trained DLNN model for estimating the occurrence of errors experienced by the color defective operators based on the DLNN normal vision color standard. The observed decrement in symbology identification should be predictive of the actual decrement in sensitivity of the human MUM-T operator with a known CVD. Validation would be performed by testing human subjects with CVDs on simulated imagery of symbology overlay plus background. Alternatively, separate DLNNs can be trained for each type of color vision deficit to create separate models of defective human color vision. Normal color imagery can then be passed through the trained models to determine color combinations of symbology and background colors that produce symbology identification errors. These DLNNs can become themselves color vision deficit standards for future studies where it is difficult to recruit sufficient numbers of human subjects with specific color deficits.

Finally, the fully-trained and validated color vision DLNNs can be embedded within the MUM-T display encoding operation. In doing so, the DLNN can monitor color symbology overlaid onto color backgrounds in real time, and anticipate color combinations where the human operator will have a high likelihood of symbology misidentification due to poor contrast. The DLNN can then be used to override the displayed symbology by inducing slight color or luminance shifts that alter the contrast ratio and serve the purpose of enhancing symbology identification. Once the background imaging no longer interferes with symbology identification, the DLNN will determine when to turn off the contrast enhancement. In essence, the DLNN can be trained to anticipate the needs of the operator and adjust automatically without distracting the operator from the mission. Similarly, an appropriately trained DLNN could be embedded that makes full-time adjustments to the MUM-T graphic display in order to enhance color selections for operators with a known CVD. The type of color vision correction would be a selectable user option on the MUM-T display.

Whether or not such enhancements ever become possible for MUM-T displays remains to be determined, however, the potential to alter graphic displays in specific ways is already available to consumers (see *Using technology to compensate for color deficiencies* section). For example, it is possible to reduce the blue light output of monitors for those individuals that have retinal degeneration exacerbated by blue light exposure, or for people who experience insomnia due to blue light overexposure. Other displays allow low-vision users to select options that alter the colors, enhance contrast, and alter font size. While these are user-selected options not specifically controlled by AI, it is likely AI can be used to make the process friendlier for the end user. In addition, consumer-based camera systems are now more amenable to AI technology. For example, DLNN-embedded cameras or camera attachments are entering the consumer market in 2018 including the Amazon Web Services DeepLens camera and the Arsenal image assistant that is a DLNN-based DSLR camera controller (Amazon Web Services, 2017; Stout, 2017).

Deep learning caveat.

While deep learning is becoming a powerful tool for interpreting visual information, it can fail to deliver the intended result if the training approach is incorrectly applied. It is critical to understand that the DLNN process interprets imagery in a vastly different manner than the

human visual system, which itself is still not fully understood. Not only are there important differences in the way humans and machines process various elements of detail, the overall interpretation of a scene can be vastly different depending on which details are considered most relevant. Even humans differ in life experiences, and their powers of observation may interpret the context of an image differently. So-called eyewitnesses may have incorrect memories of past visual experiences, even mistaking fundamental elements such as the color of an object.

Summary

Color is a perception arising from the response of the human visual system to light in the environment. Color is not a property of an object but is defined by the wavelengths of light leaving the object's surface (via emission, reflection, and/or transmission). Humans probably have evolved with color vision in order to increase the probability of survival, by aiding in locating and identifying edible food and finding healthy mates. For humans, and some other animals, color has esthetic and functional purposes. In the animal world color serves such diverse purposes as attracting mates, intimidating competition, and providing protection from predators (e.g., camouflage). For humans, color can take on symbolism, evoke emotions, and act as a mode of information coding and presentation. Its versatility has resulted in an explosion of uses in fashion, decor, business, advertising, marketing, design, art, and culture. To coin a phrase – color is everywhere. And, from a more applied viewpoint – color is information.

This white paper attempts to provide discussions that reveal and explain the complexities of color – a natural, but frequently misunderstood, attribute of the human visual system. This endeavor is considered essential to ensuring the ever-increasing usage of color in U.S. Army cockpits (and throughout the Army) will in each instance enhance, not compromise, crew capability and performance, thereby increasing the probability of mission success. It is hopeful that the myriad of professionals who read this white paper will be better prepared to design, implement, and evaluate the use of color in aeronautical systems.

Color science and its applications are broad and interdisciplinary in nature, encompassing such fields as physics, chemistry, physiology, statistics, computer science, and psychology. To fully understand color, it is necessary to explore its history, science, engineering, and use from the first cave painter, through philosophers (both religious and secular), craftsmen, artists, photographers, advertisers, psychologists, technologists, flight surgeons, and vision scientists. Modern applications of color, in or out of the cockpit, must not be driven by the often incorrect belief the addition of color to a design is a actual advancement, and the more colors added, the better. Instead, color should be employed when and where there is clear evidence that its use improves performance, e.g., decreases detection and reaction times, improves memory, and reduces error rates.

In the lengthy discussions of the many facets of color, a number of questions, problems, and issues – some specific to aviation and others more sweeping in nature – have been identified as worthy of additional research. These and a host of other studies will be required to guarantee effective color applications in aviation.

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Appendix A. Glossary

A

Absorption: The capture of electromagnetic radiation and converting its energy into internal energy (e.g., heat).

Achromatic color: A neutral color such as black, white or gray.

Achromatopsia: A hereditary visual disorder characterized by decreased vision, light sensitivity, and the complete absence of color vision.

Adaptation: The ability of the eye to adjust to different light sources or light levels.

Additive color mixing: The mixing of primary colors to produce additional colors; usually mixing associated with light. The commonly used additive primary colors are red, green and blue, which if mixed overlapped (mixed) equally produce white light.

Afterimage (color): The continuing appearance of color after the exposure to the original image has ceased. Afterimages may be positive or negative. Positive afterimages appear the same color (hue) as the original image; they often last less than half a second. Negative afterimages are of the complementary color (hue), e.g., an original green image will produce a magenta afterimage.

Analogous colors: Colors closely related in hue; usually adjacent to each other on a color wheel.

Anomalous trichromatism: A common type of inherited color vision deficiency, occurring when one of the three cone pigments is altered in its spectral sensitivity.

Anomaloscope: An optical instrument for specifying anomalous (abnormal) color vision via color matching achieved by mixing spectral lights.

Anterior segment (chamber): The front chamber of the eye formed by the cornea, iris and front surface of the crystalline lens.

Anti-collision light (strobe): A flashing aeronautical light designed to provide a red signal throughout 360 degrees of azimuth for the purpose of giving long-range indication of an aircraft's location to other aircraft.

Aqueous humor: The fluid produced by the ciliary body which fills the anterior chamber of the eye.

Area effect: The perception of colors tending to appear brighter and more vivid for large areas than they would if covering smaller areas.

Arrangement test (color): A test of color vision where the observer is required to arrange color samples by similarity in a sequential color series.

Astigmatism: One kind of refractive error in which optical power varies systematically over different radial meridians. It can be corrected with spectacles or contact lenses having a corresponding distribution of refractive powers.

Attention: The application of cognitive or perceptual resources to a task; the concentration of mental effort on sensory or mental events.

Aurora: An atmospheric phenomenon caused by collisions between air molecules and charged particles from the sun trapped in the earth's magnetic field; an example of a natural source of light.

B

Backlight: In displays, a form of illumination used in liquid crystal displays (LCDs) in which a light source is placed behind the liquid crystal layer.

Bandpass filter: A filter designed to pass frequencies within a certain range and reject (attenuate) frequencies outside that range.

Bandwidth: The range of frequencies over which a device or system performs within specified limits.

Beam splitter: An optical component (e.g., mirror or prism) used to split incident light at a designated ratio into two separate beams.

Biocular display: A term pertaining to optical devices which provide two visual inputs from a single sensor.

Binocular display: A term pertaining to optical devices which provide two visual inputs from two sensors which are displaced horizontally in space, making stereopsis possible.

Bioluminescence: A biochemical process resulting in the production of light by a living organism. Fireflies are a common example.

Bit: A basic unit of information in computing and digital communications. A bit can have only one of two values, represented as either 0 or 1.

Bit depth: The number of bits per pixel. See *Color depth*.

Black: The absence of all light. When an object absorbs all light, it looks black.

Black point: The darkest shadow in an image's histogram, with a value of 0, 0, 0.

Black Point Compensation (BPC): A color management technique for maintaining "black" as color information passes from a source to other devices (e.g., printer).

Blackbody: A theoretically ideal radiator and absorber of electromagnetic radiation.

Blind spot: The point of entry/exit of the optic nerve on the retina, insensitive to light.

Bright (color): A color having a high reflectivity.

Brightness: Attribute of a visual sensation according to which an area appears to emit more or less light; also known as lightness or value; the perceived amount of light coming from an area; one of the three standard elements of color (in addition to hue and saturation). Its colorimetric equivalent is luminance. It is a subjective attribute of light and is perceived, not measured.

Byte: A unit of digital information most commonly consisting of eight bits.

C

Candela: The Standard International (SI) unit of luminous intensity. One candela is one lumen per steradian.

Cathode ray tube (CRT): A display device that produces images by modulating the intensity of a scanning electron beam striking a phosphor coated surface (the screen).

Chroma: Purity or intensity of color; attribute of color used in the Munsell Color System to indicate the degree of departure from a gray of the same value. Correlates with dimension of saturation.

Chromatic: Having color (hue).

Chromaticity: A description of the color property of light based on hue and saturation.

Chromaticity coordinates: Coordinates specifying position in a chromaticity diagram.

Chromaticity diagram: A diagram representing the unit plane (the plane defined by the equation $X+Y+Z=1$) in a tristimulus space.

Chrominance: The color information in a signal.

Chromolithography: A printing method for producing color lithographs. It is a chemical process based on the rejection of grease by water.

CIE (International Commission on Illumination): The International Commission on Illumination (usually abbreviated CIE for its French name, Commission Internationale de l'Eclairage) is the international authority on light, illumination, color, and color spaces. It was established in 1913 as a successor to the Commission Internationale de Photométrie and is today based in Vienna, Austria.

CIE standard illuminant C: An illuminant having the relative spectral power distribution intended to represent average daylight.

CIE standard illuminant D65: An illuminant having the relative spectral power distribution intended to represent average daylight. This supersedes CIE Illuminant C as it is intended to be more representative of daylight in the UV region.

CIELAB (CIE $L^*a^*b^*$): A color space specified by the International Commission on Illumination. It describes all the colors visible to the human eye and was created to serve as a device-independent model to be used as a reference.

Ciliary muscle: The muscle within the ciliary body which controls the accommodation of the crystalline lens.

CMYK color model: A subtractive color model, used primarily in color printing; named from the initials of the four primary colors used in inks: cyan, magenta, yellow and key (black). A mixture of cyan, magenta, yellow produces a gray.

Color: A perception of light energy, usually initiated by stimulation of the cone photoreceptors in the retina.

Color appearance: The resulting color perception that includes the effects of spectrum, background contrast, chromatic adaptation, color constancy, brightness, size and saturation.

Color cast: An undesirable tint of one color in an image that can be caused by an input device, output device, or lighting conditions.

Color confusion: The perception of distinct colors appearing similar to color defective observers but would appear quite different to the color normal observer.

Color contrast: The difference between two colors; the difference in visual properties that makes an object distinguishable from other objects and the background. Colors can contrast in hue, value and saturation.

Color constancy: The general tendency of the colors of an object to be perceived as remaining constant even when the color of the illumination is changed.

Color depth: The number of bits used to indicate the color of a single pixel or the number of bits used for each color component of a single pixel.

Color difference (numerical): The difference between color coordinate values for two different samples. Quantifies the difference between two colors.

Color discrimination: The ability to differentiate between shades of a color or the difference between two or more colors when luminance has been equated or randomized.

Color gamut: An organized set or range of colors (i.e., a color space).

Color management: The process that compensates variations in color reproduction workflows by creating data files describing the unique characteristics of individual digital devices. The result enables color matching between devices, including from monitor to print, between and original photograph and a digital file.

Color matching: The action of making a color appear the same as a given color.

Color memory: The ability to successively match a new color region to a previously viewed color region.

Color model: A method of defining colors mathematically usually based on relative values of the primary colors, e.g., RGB, CIELAB, HSB, and CMYK.

Color naming: The task of placing a verbal label on the perceived color.

Color perception: Subjective impression of color, as modified by the conditions of observation and by mental interpretation of the stimulus object.

Color quality scale (CQS): A color rendering index (a quantitative measure of the ability of a light source to reproduce colors of illuminated objects) developed as a metric to overcome some of the limitations the widely used Color Rendering Index (CRI) when assessing solid-state light sources.

Color rendering: A general expression for the effect of a light source on the color appearance of objects in comparison with their color appearance under a reference light source.

Color rendering index (CRI): Measure of the amount of color change that objects exhibit when illuminated by a light source as compared with the color of the same objects when illuminated by a reference source of equivalent color temperature; value ranges between 0 to 100 percent.

Color science: The multidiscipline study of color, types of order, observations, scientific facts, physiology, and psychology to explain color reactions and interactions.

Color normal: A term referring to an observer with normal trichromatic color vision.

Color space: An organized set or range of colors (i.e., a color gamut).

Color temperature: The temperature of the perfect blackbody radiator whose chromaticity is closest to that of the light under consideration.

Color wheel: An illustrative organization of color hues around a circle, showing the relationships between primary colors, secondary colors, tertiary colors, etc.

Colorant: A dye, pigment, or other agent used to impart a color to a material.

Colorimeter: An instrument used to measure the relative intensities of red, green and blue light which is reflected or emitted (transmitted) through a color sample.

Cornea: The clear dome at the front of the eye. The cornea is the transparent collagen structure which serves as the primary focusing surface for the eye and provides about 75% of the eye's total refractive power.

Colorimetry: The science of measuring color.

Combustion: A chemical reaction in which fuels react with an oxidant compound, usually oxygen (O₂).

Complementary afterimage: A chromatic afterimage having a hue approximately the hue complementary to that of the sensation produced by the original stimulus.

Complementary colors: Two colors directly opposite each other on a color wheel; when additively mixed they produce an achromatic color.

Combiner: A beam splitter reflecting a portion of a beam of light and transmits a portion.

Cones: Photoreceptor cells located in the retina, responsible for high-acuity vision and color vision in moderate or bright light; their interaction forms the basis of color vision. Distribution of the cone photoreceptor cells varies across the retina. They are most highly concentrated in the fovea.

Confusion line: Plot on the CIE chromaticity diagram forming an isochromatic line for individuals with color deficiencies; all colors falling along this line cannot be discriminated by the observer; each of the three types of congenital color deficiencies (i.e., protan, deutan, and tritan) have their own specific color confusion characteristics.

Continuous emission (spectrum): A range of wavelengths over which energy is present with gaps.

Contrast: A measure of the luminance difference between two areas. Contrast can be formulated in different ways, e.g., contrast ratio, modulation contrast, etc.

Contrast ratio: A mathematical expression of the luminance ratio for two adjacent areas. As used herein, contrast ratio is defined as higher luminance/lower luminance.

Cool colors: The family of related colors ranging from greens through blues and violets.

Copunctal point: A point on the CIE chromaticity diagram where color confusion lines intersect for a certain dichromat; it corresponds to the missing cone primary.

Cornea: The clear dome at the front of the eye. The cornea is the transparent collagen structure which serves as the primary focusing surface for the eye and provides about 65% of the eye's total refractive power.

Correlated color temperature (CCT): A specification of the color appearance of the light emitted by a lamp, relating its color to the color of light from a reference source when heated to a particular temperature, measured in degrees Kelvin (°K).

Crystalline lens: The transparent lens within the eye that provides additional focusing power to the eye and, in the young eye, through its ability to change shape provides accommodation to view near objects.

D

Daltonization: An image processing technique that adjusts images providing viewers suffering from dichromacy to be able to recover image details and color dynamics.

Deep learning: An artificial intelligence function that imitates the workings of the human brain in processing data and creating patterns for use in decision making. Deep learning is a subset of machine learning in artificial intelligence having networks which are capable of learning unsupervised from unstructured or uncharacterized data.

Demographics: The physical characteristics of a population such as age, sex, marital status, family size, education, geographic location, and occupation.

Deutan: A type of hereditary color vision anomaly in which the patient is missing or has defective M-cones. Since M-cones have peak sensitivity in the middle wavelengths range of the visible light spectrum, deuterans are sometimes called, "green weak, or green color blind."

Deuteranopia: One of the two varieties of red-green color blindness (also known as green-dichromacy); deuteranopia results from the loss of function of the M-cones.

Dichromat: An observer who matches any spectral color with just two primaries.

Dichromatism: A color vision deficiency in which only two of the three primary colors can be distinguished due to a lack of one of the cone pigments.

Diffraction: The process by which a beam of light or other system of waves is spread out as a result of passing through a narrow aperture or across an edge.

Digital micromirror device (DMD): A matrix display where each pixel is a very small square mirror on the order of ten to twenty microns. Each mirror pixel is suspended above two electrodes driven by complementary drive signals.

Discrimination: Determination that two specific sensory stimuli are different.

Discrimination index (ID): An image quality figure-of-merit (FOM) combining contrast due to both luminance and color.

Digital Light Processing (DLP): A display device based on optical micro-electro-mechanical technology using a digital micromirror device.

Dominant wavelength: The wavelength of a spectrally pure light that, when added to a reference achromatic (white) light, will produce a combination matching the color of a specimen light.

Draper point: The approximate temperature (798 °K) above which almost all solid materials visibly glow (a dim red) as a result of blackbody radiation. It was established by chemist John William Draper in 1847.

Dye: A natural or synthetic colorant which is soluble.

Dynamic range: The extent of values from lightest to darkest.

E

Efficacy: The ratio of the light output of a lamp (lumens) to its active power (watts), expressed as lumens per watt.

Egress: The action of leaving a place (or enclosure).

Electroluminescence: An optical and electrical phenomenon in which a material emits light in response to the passage of an electric current or to a strong electric field.

Electromagnetic (EM) spectrum: The entire range of radiation extending in frequency from approximately 10²³ Hz to 0 Hz or, in corresponding wavelengths, from 10⁻¹³ cm to infinity and including, in order of decreasing frequency, cosmic-ray photons, gamma rays, x-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio waves.

Emissive source: An object that generates energy in the electromagnetic spectrum.

Equiluminant: Being of equal luminance.

Exit pupil: The region where the observer's eye(s) must be located in order to view the total field-of-view. In optics, it is the image of the aperture stop as formed from the image side of the optics.

Eye dominance: The tendency of clusters of nerve cells in the visual system to respond primarily to one eye rather than to the other.

Eyelid: The portion of moveable thin skin which serves to protect the front of the eye. The human eye is protected by an upper and lower eyelid; also referred to as "lids."

F

False color: Color added during the processing of a photographic or computer image to aid interpretation of the subject; a color rendering method used to display images in color that were recorded in non-visible parts of the electromagnetic spectrum.

Farnsworth-Munsell 100-hue test: A standard test for deficiencies of color vision in which the subject is asked to arrange a set of 100 colored chips in a circle or in a series linear rows.

Field-of-view (FOV): The maximum image angle of view visible through an optical device.

Field-sequential color system: A color display system in which the primary color information is transmitted in successive images, relying on the human vision system to fuse the successive images into a color picture.

Figure-of-merit (FOM): A numerical expression representing the performance or efficiency of a given device, material, or procedure, e.g., a metric which quantifies some aspect of image quality.

Filter: A device or material that passes signals (waves) of certain frequencies while stopping others.

Fixed-wing aircraft: A powered aircraft that has wings attached to the fuselage so that they are either rigidly fixed in place or adjustable, as distinguished from rotary-wing aircraft, like a helicopter.

Fluorescence: The absorption of light at one wavelength and its re-emission at a longer wavelength. Fluorescence plays an important role in the perceived color of many objects.

Fluorescent lighting (lamp): A low pressure mercury-vapor gas-discharge lamp that uses fluorescence to produce visible light.

Foot-candle: a measurement of light intensity and is defined as the illuminance on a one-square foot surface from a uniform source of light.

Foot-lambert (fL): A unit of luminance (photometric brightness), equal to $1/\pi$ candela per square foot, or to the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of 1 lumen per square foot.

Forward-looking infrared (FLIR): A thermal imaging sensor, where sensor output is based on infrared radiation (usually between 3-5 or 8-12 micron spectral range) generated by the external scene.

Fovea: A small microscopic depression at the center of the retina, which has the greatest density of cone photoreceptor cells, and therefore the best visual acuity. The center of an object being viewed is imaged onto the fovea, therefore this point corresponds to the straight-ahead visual direction; also referred to as the “foveola” or “fovea centralis.”

Frequency: Number of complete oscillation cycles per unit of time. The unit of frequency is the Hertz (Hz).

Full-spectrum index (FSI): A mathematical measure of how much a light source's spectrum deviates from an equal energy spectrum, based on the slope of its cumulative spectrum.

Full-spectrum color index (FSCI): A mathematical transformation of full-spectrum index into a 0 to 100 scale, where the resulting values are directly comparable to color rendering index (CRI). An equal energy spectrum is defined as having an FSCI value of 100, a “standard warm white” fluorescent lamp has an FSCI value of 50, and a monochromatic light source (e.g., low pressure sodium) has an FSCI value of 0.

G

Gamma: A measure of the amount of contrast found in an image according to the slope of a gradation curve. High contrast (steep curve) has high gamma, and low contrast (shallow curve) has low gamma.

Gamma correction: The non-linear tonal correction editing of an image's gamma curve.

Gamut (color): A measure of color rendering based upon volume in color space. See also **Color gamut**.

Gamut area (GA): The area enclosed within three or more chromaticity coordinates in a given color space.

Gamut Area Index (GAI): A measure of color rendering based upon volume in color space.

Gas discharge: An electric arc between tungsten electrodes housed in a gas-filled tube, which results in the production of light.

Glass cockpit: An aircraft cockpit that features electronic (digital) flight instrument displays, typically CRT or LCD displays, rather than traditional analog dials and gauges.

Glide path: An aircraft's line of descent to land, especially as indicated by ground radar.

Globe: A protective structures of the eye consisting of the sclera and cornea which maintain the shape of the eye; term for the eyeball.

Gloss: Shine or luster on a smooth surface; an additional parameter to consider when determining a color standard, along with hue, value, chroma, the texture of a material and whether the material has metallic or pearlescent qualities.

Glossiness: The surface characteristic of having a well-defined specular reflectance.

Gray: A color resulting from a mixture of black and white; a neutral or achromatic color.

Grayscale: A series of neutral colors, ranging from black to white; each step's color value is usually shifted by a constant amount.

H

Head-up display (HUD): Any transparent display that presents data without obstructing the user's view; does not require the pilot to look down into the cockpit.

Head-down display (HDD): A display located in the cockpit such that the pilot has to look down to the instrument panel to observe them.

Helmet-mounted display (HMD): A multimodal display system used to enhance the user's situation awareness; a device, worn on the head or as part of a helmet, which has a small display optic in front of one (monocular HMD) or each eye (binocular HMD). HMDs can present both audio and visual information.

High dynamic range (HDR): A technique used in imaging to reproduce a greater dynamic range of luminosity.

High-pressure sodium (HPS): A high-intensity discharge lamp type that uses sodium under high pressure as the primary light-producing element.

Hue: The quality of color is most closely associated with a particular wavelength. Examples of hues include red, orange, yellow, green, blue, and violet. To fully describe a color you must state not only its hue, but its saturation and brightness as well. Its colorimetric equivalent is dominant wavelength.

Human factors (HF): The science of human-machine relationships and interactions including all biomedical and psychological considerations; the science of designing the objects and environments according to human needs and capabilities.

Hunt effect: Perceived colorfulness increases with illumination level; proposed by Kodak Research Laboratories, Harrow, England, color scientist R. W. G. Hunt.

Hypoxia: A condition in which the body or a region of the body is deprived of adequate oxygen supply at the tissue level.

I

Illuminant: A light source (e.g., sun and fluorescent lamp) that has a specific spectral distribution of energy.

Illumination: Light falling on a surface.

Illusion (visual): A perception, as of visual stimulus, that differs from the way the stimulus is in reality.

Image intensification (I²): Sensor technology based on amplification of ambient light. Photons are imaged onto a photocathode which converts them into electrons. The number of electrons is

multiplied and channeled onto a phosphor screen. This is the basis of night vision imaging systems, e.g., ANVIS.

Incandescent lighting: The form of light produced by energy reaching a specific temperature, causing the filament inside a bulb to glow.

Index of refraction: A dimensionless value calculated from the ratio of the speed of light in a vacuum to that in a second medium of greater density.

Infrared (IR): A portion of the electromagnetic spectrum; an invisible band of radiation with wavelengths from 750 nanometers to 1 millimeter, infrared starts at the end of the microwave portion of the spectrum and ends at the beginning of visible light portion.

Instrument landing system (ILS): A precision runway approach aid based on two radio beams which together provide pilots with both vertical and horizontal guidance during an approach to land.

Intensity: The saturation or strength of a color; the brightness or purity of a color.

Interference: A phenomenon where two light waves from different coherent sources meet together and the distribution of energy due to one wave is disturbed by the other.

International Color Consortium (ICC) profile: A set of transforms from one color space to another.

Iris: The iris is forms the aperture of the eye, the “pupil.” The iris consists of two opposing muscles which either constrict (sphincter muscle) or dilate (dilator muscle) the iris in response to light or neurological stimuli.

Ishihara test: A test for color blindness using a set of pseudoisochromatic plates developed by Shinobu Ishihara introduced in 1917.

Isotemperature: Having the same temperature; a curve of points of isotherms is called an *isotherm*.

J

Just-noticeable difference (JND): A smallest perceived change in a physical variable.

K

Kelvin (°K): The unit in which color temperature is measured and used in imaging to define the quality of a light source by referring to the absolute temperature of a blackbody that would radiate equivalent energy.

Knot: A unit of speed of one nautical mile (6,076.12 feet or 1,852 meters) per hour.

L

L-cones: One of three cone types that contribute to human color vision. The L-cones have their peak spectral sensitivity at a longer wavelength than the other two cone types, the M-cones and S-cones.

Landolt C: A standard visual target for measuring resolution acuity. The target is constructed on a 5 x 5 grid with the gap the width of 1 grid unit. The gap is usually presented in one of four positions: right, down, left, and up (four-alternative forced choice).

Lantern test (color): An occupational-related color vision test for measuring the ability of seamen, railway personnel, and airline pilots to identify and discriminate navigational aids and signals.

Laser: A device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation; it is an acronym for "Light Amplification by Stimulated Emission of Radiation."

Lateral geniculate nucleus (LGN): A structure within the dorsal thalamus which regulates visual information received via the optic tracts from each eye.

Lay: The direction of the predominant surface pattern, usually determined by the production method.

Legibility: A measure of the quality of being readable under normal viewing conditions.

Lens: An object made of transparent material, usually with two curved surfaces, that bends (refract) or focus light rays passing through it; the transparent structure inside the eye that focuses light rays onto the retina.

Light-emitting diode (LED): A semiconductor diode that emits light when an electric voltage is applied.

Light-emitting diode (LED) display: Emissive display composed of multiple light emitting diodes arranged in various configurations which can range from a single status indicator lamp to large area x-y addressable arrays.

Lightness: One of the three dimensions describing color.

Liquid crystal display (LCD): A type of nonemissive flat panel display technology which produces images by modulating ambient light. The ambient light can be reflected or transmitted light from a secondary, external source (e.g., a backlight).

Lumen (lm): A unit measurement of the rate at which a lamp produces light.

Luminance: A photometric measure of the luminous intensity per unit area of light travelling in a given direction.

Luminance contrast: A measure of the luminance difference between two areas. Contrast can be formulated in different ways, e.g., contrast ratio, modulation contrast, etc.

Luminance transmittance: The fraction of luminance of the outside world seen through an optical component or system; usually expressed as a percentage.

Luminous: Light producing.

Lux (lx): A measure of illuminance in lumens per square meter. One lux equals 0.093 foot-candle.

M

M-cones: One of the three cone types that contribute to human color vision. The peak spectral sensitivity of the M-cones is between the peak sensitivity of the other two cone types, the L-cones and S-cones.

Macula: The central region at the posterior aspect of the retina which includes the fovea at its center. The macula has a denser distribution of cones than rods and is responsible for defined vision and color perception; also referred to as "macula lutea."

Metamerism: The property of two specimens that match under a specified illuminator (illuminant) and to a specified observer and whose spectral reflectances or transmittances differ in the visible wavelengths and may appear to be a miss match under a second specified illuminant to the same specified observer.

Mesopic vision: Vision at light levels at which both retinal cones and retinal rods are stimulated. Early twilight is within this range of illumination.

Metal halide lamp: A high-intensity discharge lamp type that uses mercury and several halide additives as light-producing elements.

Michelson contrast: One mathematical definition for contrast. It can have a maximum value of 1.0, which is the contrast of pure black stripes on a pure white background. It can have a minimum value of 0, which is the contrast of neutral gray stripes on a neutral gray background, i.e., a uniform gray field with no visible pattern.

Midtones: The range of levels (tones) which lie between highlights with detail and shadows with detail.

Microdisplay: A small, usually 1-inch diagonal or less, electronic display device that can be suspended near the eye and viewed through magnifying optics or used with higher magnification optics to project an image.

Monochromacy: The total lack of functional photopigments in the cones, which are responsible for color vision in the retina.

Monochromatic: Consisting of a single wavelength or narrow range of wavelengths.

Monochromatism: Complete color blindness in which all colors appear as shades of gray – called also monochromacy.

Moving map display: A type of navigation system that displays the user's current location at the center of a map; a symbol representing the location of the GPS device remains stationary on the display screen, while a map or chart image moves beneath the symbol.

Multifunction display (MFD): A display designed to integrate multiple functions and operational modes in a single electronic display; MFDs are part of the digital generations of modern fixed- and rotary-wing cockpits.

Munsell System (of color notation): A color model that identifies specific colors by their hue, value, and chroma; the system consists of over 3 million sample observations of what people perceive to be like differences in hue, chroma, and value.

Myopia: Nearsightedness. A kind of refractive error in which an eye, viewing a distant object, focuses the image in front of the retina; near objects are seen more clearly than distant objects.

N

Nanometer: One billionth (10^{-9}) of a meter. A common unit used for characterizing the wavelength of light.

Nanotechnology: The science of manipulating materials on an atomic or molecular scale.

Nap-of-the-earth (NOE) flight: A flight conducted at varying airspeeds as close to the earth's surface as vegetation and obstacles permit up to 25 feet above trees and vegetation in the flight path.

Neuron: A cell capable of transmitting electrochemical information within the nervous system of the body.

Neutral axis: The line representing gray scale intensity defined by the white and black points in the color space.

Neutral zone (color vision): A reference to the blue-green wavelengths appearing without color, having a gray-white luminosity, in color deficient individuals; the null-chrominance plane.

Night vision goggle (NVG): While strictly defined as second generation I^2 light amplification devices, the term often is used for later generation I^2 systems, e.g., ANVIS.

Notch filter: A filter that rejects a relatively narrow bandwidth of wavelengths while passing all others.

O

Octave band: A band of frequencies where the highest frequency is the double of the lowest frequency.

Opacity: Lacking transparency or translucence; the measure of the amount of light that can pass through a material.

Opaque: Having the property of transmitting no optical radiation.

Opponent process color theory: A color theory stating the cone photoreceptors are linked together to form three opposing color pairs: blue-yellow, red-green, and black-white; developed by Ewald Hering.

Optic chiasm: The optic chiasm is where the optic nerves from the two eyes come together and retinal ganglion cell fibers from specific parts of the retina cross to the contralateral optic tract.

Optic disc: The portion of the optic nerve visible inside the eye; sometimes referred to as the “optic nerve head.”

Optic nerve: The optic nerve is the third cranial nerve. It consists of a bundle of approximately one million retinal ganglion cell axons. The optic nerve exits the eye (or globe) posteriorly through the sclera at the lamina cribrosa.

Optic relay: A lens or lens system used to transfer a real image from one point within an optical system to another, with or without magnification.

Optic tract: The bundle of nerve fibers from the optic chiasm to the lateral geniculate nucleus.

Optical filter: A component that selectively transmits or reflects light of specific wavelengths.

Optotype: Letters, numbers, or geometric symbols of different sizes (used in visual acuity testing).

Orbit: The portion of the bony skull that surrounds and protects the eye and its supporting structures.

Organic LED (OLED): A thin film light-emitting technology that consists of a series of organic layers between two electrical contacts (electrodes) the acronym is derived from **Organic Light Emitting Device**, **Organic Light Emitting Diode**.

P

Pastels: A family of the HSV color space; frequently described as “desaturated” or “washed out” colors.

Pearlescent: Having a luster resembling that of mother-of-pearl.

Perception: A mental analysis of sensations based on prior experience and world knowledge to form a mental representation of the surrounding environment; awareness of the surrounding environment through sensory stimulation; the conscious mental registration of a sensory stimulus.

Peripheral vision: Vision near the edges of the visual field, i.e., vision in the side of the visual field, far from straight ahead.

Persistence: The time required for a phosphor’s luminance output to fall to 10% of maximum.

Phosphor: A synthetic fluorescent or phosphorescent substance, especially any of those used to coat the screens of cathode ray tubes (CRTs).

Photometer: An instrument for measuring the intensity light.

Photometry: The science of the measurement of light intensity, in terms of its perceived brightness to the human eye.

Photon: The fundamental particle of visible light.

Photopic vision: Vision under relatively high light levels when the visual response is primarily controlled by the cones.

Photoreceptor: The specialized cells in the retina designed to capture photons of light. The two types of photoreceptors are rods, which are more sensitive to low luminance conditions and motion, and cones, which are more sensitive to high luminance conditions and color.

Pigment: A finely ground, colored powder that form paint or dye when mixed with a liquid, called the vehicle.

Pilot's Night Vision System (PNVS): A forward-looking infrared sensor mounted on the nose of the AH-64 Apache aircraft which serves as an imagery source for pilotage and/or targeting.

Pixel: The basic unit of programmable color on a digital image; a contraction for "picture element."

Planckian locus: The path or locus that the color of an incandescent blackbody would take in a particular chromaticity space as the blackbody temperature changes.

Planckian radiator: A blackbody or complete radiator; the spectral power distribution of light emitted is a function of its temperature only and is described by Planck's radiation law.

Planck's law: A formula that describes the spectral density of electromagnetic radiation emitted by a blackbody in thermal equilibrium at a given temperature T . The law is named after Max Planck, who proposed it in 1900.

Plasma display: Emissive gas discharge flat panel display technology which produces light when an electric field is applied across an envelope containing a gas.

Plate test (color): A color vision test where the observer must identify a colored symbol embedded in a background (most pseudoisochromatic plates); identify which of several colors is most similar to a standard color; or identify which circle matches a gray area.

Pop-out effect: A phenomenon that occurs when a visual stimulus has mostly similar looking objects but one differing object that stands out very noticeably from the other objects in the visual field.

Posterior segment (chamber): The back chamber of the eye formed by the back surface of the crystalline lens, the ciliary body and the inside of the globe.

Primary colors: Any of a group of fundamental colors from which all other colors can be obtained by mixing e.g., red, green, and blue (RGB) and cyan, magenta, and yellow (CMY).

Primary flight display (PFD): A modern aircraft instrument dedicated to flight information.

Primary visual cortex: An area of the occipital lobe that performs the first stage of cortical visual processing (V1).

Prism: A glass or other transparent object in prism form, especially one triangular in shape with refracting surfaces at an acute angle with each other and that separates white light into a spectrum of colors.

Protan: A type of hereditary color vision anomaly in which the patient is missing or has defective L-cones. Since L-cones have peak sensitivity in the long wavelengths range of the visible light spectrum, protans are sometimes called, "red weak" or (incorrectly) "red color blind."

Protanopia: One of the two varieties of red-green color blindness (also known as red-dichromacy). Protanopia is thought to result from the loss of function of the L-cones. Protanopes display a marked loss of sensitivity to light at the long wavelength (red) end of the spectrum.

Pseudoisochromatic plate: Plate (or chart) for testing color vision on which are printed dots of various colors, brightness, saturation, and sizes, arranged such that the dots of similar color form a figure (e.g., letter, numeral, geometrical shape, or winding path) among a background of dots of another color.

Pupil: The hole or aperture in the center of the iris, which automatically adjust in size in response to light. The pupil plays an important role in the formation of the retinal image, directly controlling its illumination and quality of focus.

Purkinje shift: The tendency for peak luminance sensitivity of the human eye to shift towards the blue end of the spectrum at low illumination levels.

Purity: The degree to which a color is saturated.

Q

Quantum dot: A nanoparticle made of any semiconductor material that glows a particular color after being illuminated by light. The color they glow depends on the size of the nanoparticle.

R

Radiance: The flux of radiation emitted per unit solid angle in a given direction by a unit area of a source.

Radiometry: The science of measurement of radiant energy (including light) in terms of absolute power.

Reflection: Return of radiation by a surface, without change in wavelength. The reflection may be specular, from a smooth surface; diffuse, from a rough surface or a combination of the two.

Reflectance: The measure of light reflected off of a surface and varies according to the wavelength distribution of the light.

Refraction: The deflection from a straight path (sending) undergone by a light ray when passing obliquely from one optical medium into another.

Refractive error: An optical aberration in which the eye has too much or too little focusing power. This causes blurred vision. The three most common and familiar refractive errors are myopia (nearsightedness), hyperopia (farsightedness) and astigmatism.

Retina: The inside layer of the back of the eye that contains the photoreceptors and associated neurons; the thin neural layer at the back of the eye responsible for the initial capture and neural processing of light entering the eye.

RGB model: An additive color model in which red, green and blue light are added together in various ways to reproduce a broad array of colors. The name of the model comes from the initials of the three additive primary colors, red, green, and blue.

Rhodopsin: The light-sensitive receptor protein in the retina. When rhodopsin absorbs a photon of light it releases energy, leading ultimately to an electrical signal.

Rods: One of the two principal light receptors of the retina; highly sensitive to low variations in illumination but relatively insensitive to color differences.

S

S-cones: One of the three cone types that contribute to human color vision. The peak spectral sensitivity of the S-cones is at a shorter wavelength than that of the other two cone types, the L-cones and M-cones.

Saturation: An attribute of a visual sensation which permits a judgment to be made of the proportion of pure chromatic color in the total sensation (e.g., pink and red differ in saturation with the red being the more saturated. The spectral colors are all maximally saturated examples of their hues and differ in this respect from pastels which are desaturated. It is one of the three standard elements of color appearance (in addition to hue and brightness). Its colorimetric equivalent is purity.

Sclera: The thick outer shell of the eye. The sclera is a thick collagen structure that protects the internal structures of the eye and serves an attachment point for the extraocular muscles of the eye. It covers 95% of the eye and connects to the cornea at the limbus at the front of the eye.

Scotopic vision: A state of visual adaptation under low illumination, such as during nighttime. Under scotopic conditions, light levels are below the working range for the cone, so only the rod photoreceptors are working.

Secondary color: A color resulting from the mixing of two primary colors. There are three secondary colors: orange (red + yellow), green (yellow + blue), and violet (blue + red).

See-through display: A display that presents imagery/symbology as a virtual image, allowing the viewer to look through the imagery (in varying degrees).

Segmentation: A visual perception process that clusters image elements that “belong together;” this involves partitioning and grouping.

Shade: A mixing result of an original color to which has been added black; a shade is darker than the original color.

Shades of gray: Progressive steps in luminance where each step differs from continuous steps by a prescribed ratio, typically the square root of two.

Simultaneous color contrast: The phenomenon in which the perceived color of an area of a scene tends to take on a hue opposite to that of the surrounding area.

Situation awareness: A dynamic understanding of the individual (and vehicle or aircraft), environment, and status surrounding the individual. It is commonly divided into three levels: 1) the perception of the elements in the environment within a volume of time and space, 2) the comprehension of their meaning, and 3) the projection of their status in the near future. Lacking or having inadequate situation awareness has been identified as one of the primary factors in accidents attributed to human error.

Synapse: A gap across which a nerve cell, or neuron, can send an impulse to another neuron.

Spectral: Pertaining to the visible spectrum, thus, having to do with color.

Spectral (or spectrum) locus: The boundary edge of the of a chromaticity curve, representing the pure monochromatic wavelengths of the visible spectrum.

Spectral power distribution (SPD): At each wavelength in the visible spectrum, the power of the light at that wavelength as a proportion of its total power over the visible spectrum.

Spectrometer: An instrument for measuring a specified property as a function of a spectral variable.

Spectroradiometry: The measurement of light energy at individual wavelengths. The primary instrument used is the spectroradiometer.

Spontaneous emission: The process in which an atom or molecule transitions from an excited energy state to a lower energy state (e.g., its ground state) and emits a photon.

Standard illuminant (CIE): A theoretical source of visible light with a defined spectral power distribution.

Standard observer (CIE): The observer data for a 2-degree field-of-view, adopted by the CIE in 1931 to represent the response of the average human eye, when adapted to an equal energy spectrum. A supplementary 10-degree observer was adopted in 1964.

Stimulated emission: The process by which an incoming photon of a specific frequency can interact with an excited atomic electron (or other excited molecular state), causing it to drop to a lower energy level.

Successive color contrast: The effect created when an area of one color is viewed immediately after viewing another area color; the second viewed color is affected by the afterimage of the first color.

Subtractive color mixing: The production of colors via absorption, e.g., by use of filters, pigments, and dyes. The commonly used subtractive primary colors are cyan, magenta and yellow, and if used in an effectively equal mixture, produce black.

Surface roughness: Irregularities in the surface texture which result from the inherent action of the production process.

Symbol: An individual representation of information.

Symbology: A set of symbols. In aviation, the symbology set may include aircraft status, targeting, and navigation symbols.

Synthetic vision: A system that uses various sensors to augment the viewer's view of the outside world.

T

Tertiary color: A color that results when a secondary color is mixed with its parental primary color. There are 6 tertiary colors namely: red-orange, yellow-orange, yellow-green, blue-green, blue-violet, and red-violet.

Tint: A mixing result of an original color to which has been added white; a tint is lighter than the original color.

Tone: A mixing result of a pure color with any neutral/grayscale color including white and black; by definition all tints and shades are also considered to be tones; a tone is softer than the original color.

Translucent: Allowing light, but not detailed images to be passed through.

Transmittance (light): That fraction of the emitted light of a given wavelength which is not reflected or absorbed, but which passes through a material or object.

Transparent: Having the quality of allowing light to pass through so that objects behind can be distinctly seen.

Trichromat: A normal observer defined by the ability to match any spectral hue with a mixture of red, green, and blue primaries.

Trichromacy: Condition of possessing three independent channels for conveying color information, derived from the three different cone types.

Tristimulus values (CIE): Any color on the CIE chromaticity diagram that can be considered to be a mixture of the three CIE primaries, X, Y, Z.

Tritan: A rare color vision anomaly in which the patient has abnormal sensitivity for short wavelengths. These patients are sometimes referred to as having a blue-yellow color vision defect.

Tritanopia: Yellow-blue color deficiency. Tritanopia is thought to result from the loss of function of the S-cones.

True color: A term sometimes used to describe SuperVGA 24-bit displays capable of producing 224 (16,777,216) color variations.

U

Ultraviolet (UV): Radiant energy having wavelengths shorter than the visible wavelengths, approximately 10 to 380 nm.

V

Value: The natural lightness or darkness of a hue.

Visible spectrum: Band of electromagnetic radiation ranging from wavelengths of approximately 380 to 750 nm, corresponding to the sensitivity of the human eye.

Visual acuity: A measure of the ability of the eye to resolve spatial detail; a description of the sharpness or quality of spatial vision.

Visual cortex: Those cortical areas primarily concerned with the processing of visual information; the visual areas of the cortex are primarily located in the occipital lobe.

Visual field: The extent of space visible to an eye while it is looking at one particular point; a plot of the remaining unaided field of vision available when wearing a helmet, helmet-mounted display, etc.

Visually coupled system (VCS): A system in which the line-of-sight of the user's eyes (or head) is continuously monitored, and any change is replicated in the line-of-sight-direction of the sensor.

Vitreous humor: The fluid or gel body that fills the posterior segment (chamber) of the eye.

Vividness (color): Characteristic of intensely bright colors; having a very high degree of color saturation.

W

Warm colors: The family of colors ranging from reds through the oranges and yellows.

Wavelength: The distance in the direction of propagation between nearest points at which the wave has the same phase (e.g., peak to peak).

Waviness: The component of surface texture upon which roughness is superimposed

White: The perception of the presence of all wavelengths of visual light; The result of combining the additive primary colors (red, green, and blue). In the subtractive color mixing system, white is the result of the absence of any color.

White point: A set of tristimulus values or chromaticity coordinates that serve to define the color "white" in image capture, encoding, or reproduction; The color and intensity of a device's brightest white. With printers, this is usually the white of the paper. With scanners, the color that when scanned produces values of 255, 255, 255 (RGB). Ideally, the white point is 100 percent neutral reflectance or transmittance.

Wien's Displacement Law: A relationship between the temperature of a blackbody (T) and its wavelength of peak emission (λ_{Max}). The mathematical expression of the law is $\lambda_{\text{Max}}T = b$; where b = Wien's constant).

Workload: The hypothetical relationship between a group or individual human operator and task demands.

X

X-rays: Electromagnetic energy of very short wavelength, ranging from about 10 to 0.01 nanometers.

Appendix B. Acronyms, Abbreviations and Symbols

2D	Two-dimensional
3D	Three-dimensional
4K	An abbreviation used in the field of digital televisions that refers to a horizontal resolution on the order of 4,000 pixels and vertical resolution on the order of 2,000 pixels)
Δ	Difference between final and initial values of a variable
ΔE	Energy difference
λ	Wavelength
μm	Micron
A	Absorbance
AC	Advisor Circular
ACIC	Aeronautical Chart and Information Center
ACM	Association for Computing Machinery
ADI	Attitude Directional Indicator
AEF	American Expeditionary Forces
AFB	AFB
AFC	Alternative forced choice
AFF	Automated Flight Following
AFFDL	Air Force Flight Dynamics Laboratory
AGARD	Advisory Group for Aerospace Research and Development
AGC	Automatic gain control
AGL	Above ground level
AH	Attack helicopter
AHO	Above highest obstacle
AI	Artificial intelligence
AIAA	American Institute of Aeronautics and Astronautics
ALT	Aviation Lights Test
AM	Aerospace medicine
AMD	Age-related macular degeneration
AME	Aviation medical examiner
AMLCD	Active-matrix liquid-crystal display
AMOLED	Active-matrix organic light-emitting diode
AMPCD	Advanced Multi-Purpose Color Displays
ANN	Artificial neural network
ANSI	American National Standards Institute
ANVIS	Aviator's Night Vision Imaging System
AOPA	Aircraft Owners and Pilots Association
AR	Army Regulation
ARD	Aerospace Resource Document
ARMIS	U.S. Army Risk Management Information System
ARP	Aerospace Recommended Practice
ARVO	Association for Research in Vision and Ophthalmology

ASAMS	American Society of Aerospace Medicine
AVCATT	Aviation Combined Arms Tactical Trainer
ASI	Airspeed indicator
ASSIST	Alliance for Solid-State Illumination Systems and Technologies
ASTM	American Society for Testing and Materials
ATC	Air traffic control; Air traffic controller
ATM	Air Traffic Management
B/W	Black and white
BCE	Before the Common Era
BPC	Black Point Compensation
C	Celsius
c	Speed of light
c.	Circa (about)
cd	Candela
CAA	Civil Aviation Authority
CAAS	Common Avionics Architecture System
CAD	Colour assessment and diagnosis
CASA	(Australian) Civil Aviation Safety Authority
CCD	Charge-coupled device
CCFL	Cold cathode fluorescent lamp
CCT	Cambridge Colour Test; Cone Contrast Test; Correlated color temperature
CCNVD	Color Capable Night Vision Device
cd	Candela
CDTI	Cockpit Display of Traffic Information
CDU	Control display unit
CE	Common or Current era
CFR	Code of Federal Regulation
CH	Cargo helicopter
CIC	Color Imaging Conference
CIE	Commission International de l' éclairage (International Commission on Illumination)
CIELAB	Commission International de l' éclairage (International Commission on Illumination) $L^*a^*b^*$
CIEUVW	Commission International de l' éclairage (International Commission on Illumination) $U^*V^*W^*$
CGIV	Conference on Colour in Graphics, Imaging, and Vision
CMY	Cyan, Magenta, Yellow
CMYK	Cyan, Magenta, Yellow, black
CNN	Convolutional neural network
COM/NAV	Communication/navigation
COTS	Commercial-off-the-shelf
cPAT	Color process automation technologies
CQS	Color Quality Scale
CRI	Color rendering index

CRPMD	Combined Radar and Projected Map Display
CRT	Cathode ray tube
CSERIAC	Crew System Ergonomics Information Analysis Center
CTT	Color Threshold Tester
CUCVT	City University Colour Vision Test
CVD	Color vision deficiency
CVDPA	Colour Vision Defective Pilots Association
CW	Chief Warrant Officer
CWF	Cool white fluorescent
DIS	Draft International Standard (International Commission on Illumination)
DLP	Digital light processing
DMA	Defense Mapping Agency
DMD	Digital micromirror device
DMS	Digital Mapping System
DoD	Department of Defense
DOT	Department of Transportation
DSTO	Defence Science and Technology Agency
DTIC	Defense Technical Information Center
DTS	Data Transfer System
DVE	Degraded visual environment
EASA	European Aviation Safety Agency
ECAM	Electronic Centralized Aircraft Monitor
EFAB	Extended forward avionics bays
EFB	Electronic flight bag
EFIS	Electronic Flight Instrument System
EICAS	Engine Instrument Caution Advisory System
EM	Electromagnetic; electron microscopy
f	Frequency
FAA	Federal Aviation Administration
FALANT	Farnsworth lantern
FAR	Federal Aviation Regulation
fc	Foot-candle
FSC	Field-sequential color
FDME	Flying duty medical exam
fL	Foot-Lambert
FLCOS	Ferroelectric liquid crystal on silicon
FLIR	Forward-looking infrared
FM	Farnsworth-Munsell
FMS	Flight management system
FOM	Figure of-merit
FSCI	Full-spectrum color index
FSXXI	Flight School XXI
FWHM	Full width at half maximum

GA	Gamut area
GaAs	Gallium arsenide
GAI	Gamut Area Index
GaP	Gallium phosphide
GIS	Geographic information system
GPS	Global Positioning System
GPU	Graphic processor unit
h	Plank's constant
HDD	Head-down display
HDR	High Dynamic Range
HDTS	Helmet Display and Tracker System
HDTV	High definition television
He-Ne	Helium-Neon
HF	Human factors
HFACS	Human Factors Accident Classification System
HFE	Human factors engineering
HFES	Human Factors and Ergonomics Society
HFM	Human factors and medicine
HMCS	Helmet Mounted Cueing System
HMD	Helmet-mounted display
HP	High-pressure
HRR	Hardy Rand and Rittler
HSB	Hue, saturation, brightness
HSI	Horizontal Situation Indicator
HSL	Hue, saturation, lightness
HSS	Helmet Sighting System
HSV	Hue, saturation, value
HUD	Head-up display
Hz	Hertz
I ²	Image intensification
IBM	International Business Machines (Corporation)
ICAO	International Civil Aviation Organisation
ICC	International Color Consortium
ICSE	International Conference on Software Engineering
ID	Discrimination index
IDRC	International Display Research Conference
IEA	International Ergonomics Society
IEEE	Institute of Electrical and Electronics Engineers
IERW	Initial Entry Rotary Wing
IES	Illuminating Engineering Society
IFR	Instrument flight rules
IHADSS	Integrated Helmet Display Sight System
IHU	Integrated Helmet Unit
IIDS	Integrated Instrument Display System

ILIR	Independent Laboratory Innovative Research
ILS	Instrument landing system
IMC	Instrument meteorological conditions
IMCL	International Conference on Machine Learning
in	Inch
INVIS	Integrated Night Vision Imaging System
IOSR	International Organization of Scientific Research
IPD	Interpupillary distance
IR	Infrared
ISAL	International Symposium on Automotive Lighting
ISAM	Indian Society of Aerospace Medicine
ISCAS	International Symposium on Circuits and Systems
ISCC	Inter-Society Color Council; Intrasociety Color Console
ISO	International Organization for Standardization
ISTC	Institute of Cognitive Sciences and Technologies
ITT	Interstage turbine temperature
JAA	Joint Aviation Authorities
JAMA	Journal of the American Medical Association
JND	Just-noticeable difference
JTRS	Joint Tactical Radio System
K	Kelvin
kHz	Kilohertz
KIAS	Knots-indicated air speed
L	Long wavelength (red); Luminance
LASER	Light Amplification by the Stimulated Emission of Radiation
LCD	Liquid crystal display
LED	Light-emitting diode
LGN	Lateral geniculate nucleus
LMS	Long-medium-short (color space)
LOC	Instrument landing system localizer
LWIR	Long-wave infrared
lx	Lux
m	Meter
mm	Millimeter
M	Medium wavelength (green)
M-DSA	Modernized Day Sensor Assembly
M-TADS	Modernized Target Acquisition and Designation System
MANMED	Manual of the Medical Department
MCP	Microchannel plate
MEDEVAC	Medical evacuation
MFD	Multifunction display
MH	Multi-mission

MIL-HDBK	Military handbook
MIL-PRF	Military Performance Specification
MIL-STD	Military Standard
MILES	Multiple Integrated Laser Engagement System
MIT	Massachusetts Institute of Technology
MOS	Military operational specialty
MPD	Multipurpose display
MUM-T	Manned-unmanned teaming
NAMRU-D	Naval Medical Research Unit – Dayton
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NATS	National Air Traffic Services Ltd.
NAVMED	Navy Medicine
NAWC	Naval Air Warfare center
NBC	National Broadcasting Company; Nuclear, biological, and chemical
NBS	National Bureau of Standards
ND	Navigation display
NICU	Newborn intensive care unit
NIGMS	National Institute of General Medical Sciences
NIH	National Institute of Health
NIPS	Neural information processing systems
NIR	Near-infrared
NIST	National Institute of Standards and Technology
NLPIP	National Lighting Product Information Program
nm	Nanometer
NOAA	National Oceanic and Atmospheric Administration
NOE	Nap-of-the-earth
NOS	National Ocean Service
NORDA	Naval Ocean Research and Development Activity
Nr	Number of rotations (Main rotor speed)
NSM	Natural Semantic Metalanguage
NSMC	(U.S.) Naval Submarine Medical Center
NSMRL	Naval Submarine Medical Research Laboratory
NTSB	National Transportation Safety Board
NVG	Night Vision Goggle
NVIS	Night Vision Imaging System
OAM	Operations, Administration, and Maintenance
OCR	Optical character recognition
OCS	Officer Candidate School
OH	Observation helicopter
OIF	Operation Iraqi Freedom
OLED	Organic light-emitting diode
ONS	Operational Needs Statement
OSHA	Occupational and Safety Health Administration

P	Phosphor
PAPI	Precision Approach Path Indicator
PC	Personal computer
PC LED	Phosphor-converted light emitting diode
PDP	Power distribution panel
PFD	Primary Flight Display
PIP	Pseudoisochromatic plate
PIPIC	Pseudoisochromatic plate Ishihara compatible
PMDS	Projected Map Display Set
PNVS	Pilot Night Vision System
POH	Pilot Operating Handbook
QSM	Quality Microsystems
RAF	Royal Air Force
RCCT	Rabin Cone Contrast Test
RGB (R-G-B)	Red, Green, Blue
RIT	Rochester Institute of Technology
RMS	Root-mean-square
ROI	Region of interest
ROTC	Reserve Officers' Training Corps
ROYGBIV	Red, Orange, Yellow, Green, Blue, Indigo, Violet
RPM	Revolutions per minute
RSD	Retinal scanning display
RTCA	Radio Technical Commission for Aeronautics
RTO	Research and Technology Organization
S	Short wavelength (blue)
SACAA	South African Civil Aviation Authority
SAE	Society of Automotive Engineers
SAM	School of Aerospace medicine
SAR	Search and rescue; Synthetic aperture radar
SI	Standard International
SOAR	Special Operations Aviation Regiment
SODA	Statement of Demonstrated Ability
SPD	Spectral power distribution
Sr	Steradian
STD	Standard
SuperVGA	Super Video Graphics Array
SWIR	Short-range infrared
SWOT	Strengths-Weaknesses-Opportunities-Threats
SXGA	Super Extended Graphics Array
T	Temperature; Transmittance
TAC MAP	Tactical map

TADS	Target Acquisition and Designation System
TAWS	Terrain Awareness and Warning System
TC	Training Circular
TCAS	Traffic Alert and Collision Avoidance System
TFT	Thin-film transistor
TH	Training helicopter
TM	Technical Manual
TOP	Test Operations Procedure
TSO	Technical Standard Order
UAS	Unmanned aerial systems
UCS	Uniform Color Scale
UFD	Up Front Display
UH	Utility helicopter
USAAC	United States Army Air Corp
USAARL	United States Army Aeromedical Research Laboratory
USABAAR	United States Army Board for Aviation Accident Research
USACRC	United States Army Combat Readiness Center
USAF	United States Air Force
USAFSAM	United States Air Force School of Aerospace Medicine
USASC	United States Army Safety Center
USMA	United States Military Academy
USN	United States Navy
UV	Ultraviolet
V	Value
V1	Primary visual cortex
VASI	Visual Approach Slope Indicator
VCOP	Virtual Cockpit Optimization Program
VDT	Visual display terminal
VFR	Visual flight rules
VHF	Very high frequency
VLSI	Very-large scale integration
VNTSC	Volpe National Transportation Systems Center
VOR	VHF Omni Directional Radio Range
VRD	Virtual retinal display
WCCVT	Waggoner Computerized Color Vision Test
WPAFB	Wright Patterson Air Force Base
WTDS	Worldwide Phosphor Type Designation System
WWI	World War One
WWII	World War Two



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