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Standard Practice

**COLOR USE IN AIR TRAFFIC
CONTROL SYSTEM DISPLAYS**

FOREWORD

This standard is approved for use by all departments of the Federal Aviation Administration (FAA).¹ It provides color-usage requirements and guidelines for air traffic control (ATC) applications that may serve as design requirements for all future ATC acquisitions and upgrades of current systems involving primary displays in tower, terminal, en route, oceanic, and other air traffic operations facilities. It may be extended to auxiliary displays, such as those depicting weather systems and traffic management systems.

Color has become an integral part of ATC displays as they have evolved from monochromatic radar displays to full-color, complex interfaces that require operators to discriminate, identify, and locate many colors to make effective use of the information displayed. That information must be legible too, regardless of its color. In accordance with the Americans with Disabilities Act (ADA) of 1990 and the Rehabilitation Act of 1973, the FAA and the Civil Aerospace Medical Institute (CAMI) screen normal color-vision (NCV) and color-vision deficient (CVD) ATC candidates to determine if their color vision is sufficient to perform mission tasks. The Air Traffic Color Vision Test (ATCOV) was developed by CAMI to determine which CVD candidates have sufficient color vision to complete ATC mission tasks on current ATC systems and to screen out others who do not.

This standard incorporates a standard color palette that CAMI has developed to fulfill requirements established by the ADA and the Rehabilitation Act (Gildea, Milburn, & Post, 2018; Gildea et al., in press). The colors are specified in terms of their Commission Internationale de l'Eclairage (CIE) normalized luminances and chromaticity coordinates, as well as their corresponding computer-industry standard red, green, and blue (sRGB) values. It provides a standard color set for coding *critical information* (see definition in [Section 3](#)) on non-tower primary ATC displays. The use of sRGB values and related requirements in this standard will facilitate accurate reproduction of the standard color set in the field.

Human Factors Standards Program

The FAA's Human Factors Division (ANG-C1) under the Assistant Administrator for NextGen, Portfolio Management and Technology Development Office, has program management responsibility and coordinates the development and maintenance of FAA Human Factors standards that are levied in acquisition programs. ANG-C1 point of contact: Dan Herschler, 202-267-9853

Comments, suggestions, or questions on this document should be addressed to Human Factors Division, ANG-C1, 800 Independence Ave., SW, Washington, DC 20591, or emailed using the form under Contact Us at the bottom of the page at <https://www.hf.faa.gov>.

¹ The requirements and criteria contained in this standard do not apply to the design approval of aircraft, which is covered currently in 14 CFR Parts 21, 23, 25, 27, and 29.

Table of Contents

1	SCOPE	7
1.1	Purpose.....	7
1.2	Application.....	7
1.3	Use of shall and should	7
1.4	Measurement units	7
1.5	Use of color figures.....	8
1.6	Change record	8
2	APPLICABLE DOCUMENTS	8
2.1	General.....	8
2.2	Government documents	8
2.3	Non-government documents	8
2.4	Order of precedence	9
3	DEFINITIONS.....	10
4	GENERAL REQUIREMENTS	15
4.1	Acceptable uses for color on visual displays	15
4.1.1	Attention	15
4.1.2	Identification	16
4.1.2.1	Nominal color coding	16
4.1.2.2	Ordinal color coding.....	16
4.1.2.3	Interval color coding.....	16
4.1.2.4	Ratio color coding	18
4.1.3	Segmentation.....	18
4.2	Color code critical information redundantly.....	20
4.2.1	Redundant coding illustrations	20
4.2.2	Don't use brightness coding as a redundant coding dimension.....	22
4.3	Use color purposefully.....	22
4.4	Use color-code meanings consistently.....	23
4.5	Maintain consistent color appearance.....	23
4.6	Don't create chromostereopsis.....	25
4.7	Don't make color hard to discern due to small stimulus size	27
4.8	Don't require accurate peripheral color discrimination and recognition	27
4.9	Acceptable ways to use temporal modulation of color	28
4.10	Consider the viewing environment's ambient illumination.....	28
4.11	Avoid large mismatches between display and environmental luminances.....	30
5	DETAILED REQUIREMENTS	31
5.1	Color requirements unique to terminal systems.....	31
5.2	Use the standard meanings for common ATC colors	31
5.3	Provide ability to display a key for non-stereotypical color-coding sets.....	31
5.4	Use black or gray as the background color.....	31
5.4.1	Use a black background for low ambient-illumination conditions.....	32
5.4.2	Use a gray background for normal or high ambient-illumination conditions.....	32
5.5	Luminance-contrast requirements for text, symbols, and icons	32
5.6	Height requirements for text, symbols, and icons.....	33
5.6.1	Text or graphics embedded within symbols	33

5.6.2	Individual letters, symbols, and icons.....	33
5.6.3	Short text strings	33
5.6.3.1	Rapid reading not required	33
5.6.3.2	Rapid reading required	33
5.6.4	Long text strings	33
5.7	Minimum acceptable color difference among search targets	34
5.8	Minimum acceptable difference for discriminable spatially-adjacent colors	35
5.9	Maximum permissible color-coding set size	35
5.10	Don't use "spectrally extreme" blues on dark backgrounds	36
5.11	Accommodate operators with color-vision deficiencies.....	37
5.12	Color selection for color-coding sets – general guidance.....	37
5.13	FAA standard palette for color coding critical information.....	37
5.13.1	Foreground objects.....	37
5.13.2	Weather severity.....	37
5.13.3	Palette changes for ambient illumination greater than 200 lux.....	38
5.14	Requirements for colors that aren't part of the FAA standard palette.....	38
5.15	Allowing operators to customize colors	39
5.15.1	Disallow changing the chromaticity of alerts and other critical information.....	39
5.15.2	Allowable method for changing the chromaticity of non-critical information ...	39
5.15.3	Allow adjustment of display's peak white luminance	39
5.15.4	Allow adjustment of object luminances	39
5.15.5	Allowable method for changing object luminances.....	39
5.15.6	Allow single-point and global changes	39
5.15.7	Allow operators to save customized color sets	40
5.15.8	Allow operators to restore customized color sets.....	40
5.15.9	Provide a color-reset function	40
5.15.10	Perform an automatic color-reset on restart	40
5.15.11	Provide an sRGB preset for operators.....	40
5.16	Display hardware color requirements	40
5.16.1	Conform to sRGB.....	40
5.16.1.1	sRGB white-point chromaticity accuracy.....	40
5.16.1.2	sRGB-primary chromaticity accuracy	40
5.16.2	Provide a software-triggered sRGB preset.....	41
5.16.3	Maximum black luminance.....	41
5.16.4	Minimum peak-white luminance	41
5.16.5	Luminance non-uniformity at operator eye-position	41
5.16.6	Chromaticity non-uniformity at operator eye-position	41
5.16.7	Luminance non-uniformity off-axis.....	41
5.16.8	Chromaticity non-uniformity off-axis.....	41
5.16.9	Pixel fill factor for LCDs	42
5.16.10	Minimum LCD pixel density	42
5.16.11	Impermissible pixel faults	42
5.16.11.1	Stuck lines or rows of pixels.....	42
5.16.11.2	Visible temporal variability of lines or rows of pixels	42
5.16.11.3	Visibly stuck or temporally variable pixels, pixel subareas, and subpixels...	42
5.16.12	Required temporal characteristics	42

5.16.13	Provide display-calibrator compatibility	42
6	NOTES.....	43
6.1	Intended application.....	43
6.2	Tailoring.....	43
6.2.1	General guidance	43
6.2.2	Tailoring to reduce cost	43
6.2.3	Joint responsibility	43
6.2.4	Process	44
6.3	Implementers' points of reference	44
	APPENDIX A. COLOR CALCULATIONS.....	45
A.1	Size-correction coefficients for Eqn. 1	45
A.2	Plotting and evaluating confusion lines	45
A.2.1	Drawing the CIE 1976 UCS diagram	45
A.2.2	Converting sRGB values to u' and v'	47
A.2.3	Plot the colors' u' and v' coordinates	47
A.2.4	Drawing confusion lines	48
A.2.5	Interpreting confusion lines	51
	APPENDIX B. DISPLAY COLOR CALIBRATION.....	53
B.1	Purpose.....	53
B.2	Calibration schedule.....	53
B.3	Calibration tags	53
B.4	Calibration process.....	53
B.5	Calibrator calibration	54
B.6	Operator adjustment of display controls	54
	APPENDIX C. Designing ordinal, interval, and ratio color codes.....	55
C.1	Choosing specific sRGB values to represent color names.....	55
C.2	Choosing the perceptual dimension and endpoints.....	56
	APPENDIX D. ACRONYMS AND ABBREVIATIONS	58
	APPENDIX E. REFERENCES	59
	CONCLUDING MATERIAL	64

Table of Figures

FIGURE 4.1.1-1.	Pop-out effect illustration.....	15
FIGURE 4.1.2.3-1.	Interval color coding, as used in a thermal image.....	16
FIGURE 4.1.2.3-2.	Interval color coding, as used on a weather display to show dBZ.....	17
FIGURE 4.1.2.4-1.	Ratio color coding, as used on ERAM to show history trails.	18
FIGURE 4.1.3-1.	Regional segmentation, as used on ERAM to show sector boundaries.	19
FIGURE 4.1.3-2.	Pattern segmentation, as used on STARS to distinguish owned aircraft (white) from others (green).	19
FIGURE 4.2.1-1.	Redundant coding using color and shape.....	20
FIGURE 4.2.1-2.	Redundant coding using color and size.....	20
FIGURE 4.2.1-3.	Redundant coding using color and pattern.....	20
FIGURE 4.2.1-4.	Redundant coding using color, shape, position, and temporal modulation.	21

FIGURE 4.2.1-5. Redundant STARS coding using color, text content, position, and temporal modulation.	21
FIGURE 4.2.1-6. Redundant coding using color, shape, and position.	22
FIGURE 4.2.1-7. Redundant coding using color, shape, position, and size.	22
FIGURE 4.5-1. Simultaneous color-contrast illustration.	23
FIGURE 4.5-2. Color assimilation illustration.	24
FIGURE 4.5-3. A potentially troublesome weather depiction.	24
FIGURE 4.5-4. Stimulus color and legibility on solid, striped, and stippled backgrounds.	25
FIGURE 4.6-1. Chromostereopsis illustration.	26
FIGURE 4.6-2. Effects of a gray background on chromostereopsis and legibility of blue.	26
FIGURE 4.7-1. Effects of stimulus size on color appearance.	27
FIGURE 4.10-1. Effects of ambient illumination on an electronic display's color gamut.	29
FIGURE A.2.1-1. CIE 1976 UCS diagram.	46
FIGURE A.2.3-1. The FAA standard palette's foreground colors.	47
FIGURE A.2.4-1. Protan confusion lines for the FAA standard palette's foreground colors.	49
FIGURE A.2.4-2. Deutan and tritan confusion lines for the FAA standard palette's foreground colors.	50
FIGURE A.2.4-3. Protan, deutan, and tritan confusion lines for the FAA standard palette's foreground colors.	51
FIGURE B.3-1. Example of a calibration tag.	53

Table of Tables

TABLE 5.6-I. Height requirements for text, symbols, and icons, expressed as arcmin of visual angle subtended at the operator's expected viewing distance.	34
TABLE 5.13.2-I. FAA standard palette: Foreground colors. (See Appendix A for graphical representations.)	38
TABLE 5.13.2-III. FAA standard palette: Weather colors.	38
TABLE A.2.3-I. sRGB primaries.	48
TABLE A.2.4-II. Recommended copunctal points.	48
TABLE C.1-I. The 24 reliably named colors from Derefeldt and Swartling (1995).	55

1 SCOPE

1.1 Purpose

This standard provides color-usage requirements and guidelines for electronic visual air traffic control (ATC) displays. It is intended for: (1) Software engineers who write computer programs that use color to communicate with ATC operators; (2) Hardware engineers who select the specific displays on which the colors will appear; (3) Human factors practitioners who work with the software and hardware engineers to ensure that operator visual needs and limitations are accounted for and who are responsible for tailoring the applicable requirements of this standard, as appropriate for each acquisition program; (4) Acceptance-testing personnel who ensure that newly received displays meet required color specifications; and (5) Maintenance personnel who are responsible for ensuring the displays maintain proper adjustment so the intended colors appear on them.

1.2 Application

This standard provides requirements and guidelines that may serve as design requirements for all future ATC acquisitions and upgrades of current systems involving primary displays in tower, terminal, en route, oceanic, and other air traffic operations facilities. It may be extended to auxiliary displays, such as those depicting weather systems and traffic management systems.²

1.3 Use of shall and should

This document contains both requirements and recommendations. Most paragraphs in Sections 4 and 5 are structured as “shall” or “should” statements. “Shall” indicates requirements; “should” indicates recommendations. “Shall” statements are highlighted by italicized bold text (i.e., ***shall***).

“Shall” statements describe requirements that originate from, or are comparable to, statements in authoritative sources such as Federal Aviation Administration (FAA) orders, standards, and military specifications. “Should” statements are recommendations that represent best practices that apply in many situations. Qualified human factors practitioners who are technical experts in the program office (FAA or engineering support contractor personnel) and are familiar with the subject matter and relevant program requirements in system specification documents must determine the applicability and compliance with “should” statements in Sections 4 and 5. It is unacceptable and not in the FAA’s interest to allow integration contractors to comply or fail to comply with “should” statements in Sections 4 and 5 at their own discretion. In addition, the human factors practitioner in the program office must coordinate closely with the test organization to ensure that appropriate test methods and test cases are employed to verify compliance with all applicable (“tailored-in”) requirements (“shalls”) and recommendations (“shoulds”). Tailoring is addressed in more detail in Section 6 of this document.

1.4 Measurement units

Measurements and dimensions used in this document are expressed in Système International (SI) units.

² The requirements and criteria contained in this standard do not apply to the design approval of aircraft, which is covered currently in 14 CFR Parts 21, 23, 25, 27, and 29.

1.5 Use of color figures

Readers should be aware that color figures in this document may not look exactly as intended because of differences in color rendering among displays. Discrepancies are even more likely if paper copies are printed.

1.6 Change record

This is the first version of this document.

2 APPLICABLE DOCUMENTS

2.1 General

The documents listed in Section 2 are specified in Sections 4 and 5 and Appendices A and B of this standard in a manner that indicates clearly that they must be consulted to ensure compliance with a requirement. Section 2 omits documents cited solely to justify a requirement, as sources for additional information, or as examples. Documents like these are listed in [Appendix E](#).

The documents listed in Section 2 form a part of this document to the extent specified herein. Unless specified otherwise, the issues of these documents are those cited in the solicitation or contract.

2.2 Government documents

FAA JO 7210.3Z - Air Traffic Organization Policy: Facility Operation and Administration (10 November 2015).

(Copies of this document are available online at:
https://www.faa.gov/documentLibrary/media/Order/7210.3Z_Bsc_w_Chg_1-3_dtd_4-27-17.pdf
.)

2.3 Non-government documents

COMMISSION INTERNATIONALE DE L'ECLAIRAGE (CIE)

CIE 15:2004 - *Colorimetry* (3rd edition, 2004). Vienna, Austria: Commission Internationale de l'Eclairage.

(Copies of this document are available online at: <https://archive.org/details/gov.law.cie.15.2004>.)

INTERNATIONAL COMMITTEE FOR DISPLAY METROLOGY

IDMS 1.0.3 - *Information display measurements standard* (Version 1.0.3, 1 June 2012). Campbell, CA: Society for Information Display.

(Copies of this document are available online at: <http://www.icdm-sid.org/>.)

INTERNATIONAL ELECTROTECHNICAL COMMISSION (IEC)

IEC 61966-2-1:1999 - *Multimedia systems and equipment - Colour measurement and management - Part 2-1: Colour management – Default RGB colour space – sRGB* (1999). Geneva, Switzerland: International Electrotechnical Commission.

(Copies of this document may be purchased online at: <https://webstore.iec.ch/publication/6169>. A reliable description of the relevant requirements that may be available more readily can be found at the [Wikipedia entry for sRGB](#).)

2.4 Order of precedence

In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

Note: FAA Order JO 7210.3Z includes specific requirements for use of color in terminal ATC displays currently. These requirements pre-date this standard's development and should be followed as long as FAA Order JO 7210.3 continues in force and continues to prescribe uses of color in ATC displays. In all other respects, this standard's requirements concerning the use of color in ATC displays take precedence over other FAA and industry standards, except as provided by applicable law or regulation. FAA Orders apply internally to FAA organizations and are not invoked as requirements in system acquisition contracting; therefore, it would be appropriate for the FAA program management office to invoke the requirements contained in FAA Order JO 7210.3 by copying the material verbatim from the Order into applicable sections of the system requirements that are included in the acquisition package.

3 DEFINITIONS

Achromatic: Colorless and having no obvious hue. Black, gray, and white are achromatic colors.

Active area: The area of an electronic display screen on which images may be created. The screens for most electronic display technologies have inactive edges, so their active areas are smaller than their total screen areas.

Advisory: A signal that indicates a safe or normal configuration, condition of performance, or operation of essential equipment, or attracts attention and imparts information for routine action purposes (FAA-HF-STD-001B, 2016).

Alarm: A signal that indicates an unusual condition exists that warrants immediate attention and immediate action to prevent loss of life, equipment damage, or disruption of national airspace system operations.

Alert: A signal that indicates a condition relating to the effective performance of duties. The condition or message requires the operator or maintainer to take immediate action or indicates that a significant update in information necessary for the effective performance of duties is available. (FAA-HF-STD-001B, 2016).

Ambient illumination: Illumination due to lighting in the viewing environment, measured in the plane of a display (CIE, 2011).

Aspect ratio: The ratio of a display-screen active area's width to its height.

Auxiliary display: A secondary display that provides information that supplements an operator's primary tasks and decisions.

Brightness: The aspect of color perception that refers to the extent to which a stimulus appears to emit either more or less light, that is, appears bright or dim.

Candela: The SI base unit for photometry: luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \cdot 10^{12}$ Hz and has a radiant intensity in that direction of $1/683 \text{ W} \cdot \text{sr}^{-1}$. Units = $\text{lm} \cdot \text{sr}^{-1}$ (CIE, 2011). Its SI abbreviation is cd.

Caution: A signal that indicates the existence of a condition requiring attention but not immediate action or a written notice given when a situation might result in damage to, or destruction of, equipment or systems. (FAA-HF-STD-001B, 2016).

Chromatic: An adjective that refers jointly to the two aspects of color perception that are independent of brightness; namely, hue and saturation.

Chromaticity: The noun form of *chromatic*.

Chromaticity coordinate: One of a pair of numbers that are used to define a color's chromatic aspects operationally as coordinates on a chromaticity diagram.

Chromaticity diagram: A two-dimensional figure that represents the chromatic aspects of color operationally. Equivalently, a plane diagram in which points specified by chromaticity coordinates represent the chromaticities of color stimuli (CIE, 2011).

Chromaticity gamut: The range of chromaticity coordinates a visual display can produce, depicted usually as a triangle on a chromaticity diagram. The triangle's corners are the locations of the RGB primary's chromaticity coordinates.

Chromostereopsis: An appearance of spatial depth differences among stimuli, caused usually by using highly saturated stimuli that differ widely in hue.

CIE standard illuminant D₆₅: The relative spectral power distribution representing a phase of daylight with a correlated color temperature of approximately 6500 Kelvins (CIE, 2011).

CIE 1976 uniform chromaticity scale (UCS) diagram: A chromaticity diagram defined in CIE 15:2004 and intended to represent perceived color spacing and differences among colors having equal luminance in an approximately uniform way. Its x-axis is labeled u' ; its y-axis is labeled v' .

CIE 1976 u' chromaticity coordinate: A color's abscissa value when it is plotted on the CIE 1976 uniform chromaticity scale (UCS) diagram.

CIE 1976 v' chromaticity coordinate: A color's ordinate value when it is plotted on the CIE 1976 uniform chromaticity scale (UCS) diagram.

Color: A term that can be used in either of two senses: *Perceived* color is a characteristic of visual perception that can be described by the attributes of brightness, hue, and saturation. *Psychophysical* color specifies a color stimulus in terms of operationally defined values, such as luminance and chromaticity coordinates (CIE, 2011).

Color assimilation: A perceptual effect where the perceived colors of a background and stimuli presented against it shift toward each other.

Color coding: The use of color to convey the meanings of data that are presented dynamically, intermingled, or distributed irregularly on a visual display.

Color contrast: The perceived difference between two colors.

Color gamut: The range of luminances and chromaticity coordinates a visual display can produce, depicted sometimes as a three-dimensional figure.

Color space: A psychophysical model based on measurable attributes of color in which the range of colors humans can perceive is conceptualized as a three-dimensional space and any color can be specified operationally by stating its three Cartesian coordinates in that space.

Complementary color: The color opposite another on a chromaticity diagram. For example, the complements of most reds are cyans; the complements of most greens are magentas (or purples); the complements of most blues are yellows.

Cone: A photoreceptor in the human retina that produces signals that provide the basis for color vision.

Confusion line: A line drawn on a chromaticity diagram such that any chromaticity coordinates lying on it will be difficult or impossible for people having one of the three main classes of color-vision deficiency (i.e., protan, deutan, or tritan) to discriminate. There are three possible points of origin for confusion lines, each corresponding to one of the three main classes of color-vision deficiency.

Contrast: In the perceptual sense: assessment of the difference in appearance of two or more parts of a field seen simultaneously or successively. In the physical sense: quantity intended to correlate with the perceived brightness contrast, usually defined by one of a number of formulae which involve the luminances of the stimuli considered. (CIE, 2011).

Copunctal point: A point of origin for confusion lines corresponding to one of the three main classes of color-vision deficiency: protan, deutan, and tritan.

Correlated color temperature: The temperature of a blackbody radiator having a chromaticity that is nearest the source's on a chromaticity diagram having u' and $2/3v'$ as its axes. Its units are Kelvins, which are abbreviated as K. (CIE, 2011).

Critical information: Information essential to an operator's ability to accomplish the task in accordance with system or mission requirements, thereby avoiding adverse effects on system safety, effectiveness, efficiency, and reliability.

Decibel: A base-10 logarithmic unit used to express the ratio of two quantities, one of which is usually a standard reference value. Its standard abbreviation is dB.

Density slicing: Grouping adjacent levels of a continuous variable into an ordinal-, interval-, or ratio-scale sequence and depicting all members of each group identically.

Deutan: A color-vision deficient person whose medium-wavelength-sensitive (M) cones are either absent (deuteranopia) or have abnormal spectral sensitivity (deuteranomaly), thereby degrading their perception of green colors and discrimination between green and red colors.

Display primary: One of an electronic color display's independent color channels, which are red, green, and blue, typically.

Focal color name: One of the 11 basic color names that are used reliably to describe color by people having normal color vision, across most cultures and languages: *red, pink, orange, yellow, brown, green, blue, purple, black, white, and gray* (in English).

Fovea: The retina's central area, where short-, medium-, and long-wavelength-sensitive (S, M, and L) cones are most prevalent, subtending roughly 5 degrees visually. Visual acuity and color perception are best within the fovea.

Hue: The attribute of a visual perception according to which an area appears to be similar to one of the colors: red, yellow, green, and blue, or to a combination of adjacent pairs of these colors considered in a closed ring (CIE, 2011).

Illuminance: An amount of illumination, measured and expressed preferably in SI units as lumens per square meter (lm/m^2). The lm/m^2 is called *lux* and abbreviated lx in the SI system.

Illumination: Light arriving at a surface.

Lumen: The SI unit of luminous flux, equal to the luminous flux emitted in unit solid angle (steradian) by a uniform point source having a luminous intensity of 1 candela (CIE, 2011). Its SI abbreviation is lm.

Luminance: The psychophysical correlate of brightness, measured and expressed preferably in SI units as candelas per square meter (cd/m^2).

Luminance-contrast ratio: The ratio of one luminance to a lesser one.

Luminous flux: Quantity derived from radiant flux by evaluating the radiation according to its action upon a CIE standard photometric observer (CIE, 2011).

Monochromatic: Having only one color.

Native resolution: The highest spatial resolution available from a display consisting of physically discrete pixels that are addressed individually, expressed as the number of addressable pixels it possesses horizontally and vertically (in that order, usually).

Normalized luminance: Luminance that has been normalized relative to a maximum value to yield values ranging from 0 to 100%. For cases herein, the normalization constant is the display's peak white luminance.

Peak white luminance: The luminance produced when the largest possible RGB values (255, 255, 255, usually) are sent to the display, that is, the maximum luminance the display can produce, given its current state of adjustment.

Photopic: An adjective referring to stimuli that stimulate cones only or mainly.

Population stereotype: An option that is chosen most often by members of a given population, or an expectation, interpretation, or manner of perceiving, thinking, or behaving that is typical within the population.

Primary display: A display that provides information essential to an operator's primary tasks and decisions.

Protan: A color-vision deficient person whose long-wavelength-sensitive (L) cones are either absent (protanopia) or have abnormal spectral sensitivity (protanomaly), thereby degrading their perception of red colors and discrimination between red and green colors.

Pseudocolor: The use of varying hues (and varying saturations and/or brightnesses, possibly) to depict data from one continuous variable.

Radiant flux: Power emitted, transmitted, or received in the form of radiation (CIE, 2011).

Receptive field: The receptive fields mentioned in this document are those of retinal ganglion cells that have a center-surround configuration and are red/green or yellow/blue opponent.

Rod: A photoreceptor in the human retina that produces signals that provide the basis for night vision, which is achromatic.

Saturation: The colorfulness of an area judged in proportion to its brightness (CIE, 2011). Desaturated colors appear pale; saturated ones appear vivid.

Scotopic: An adjective referring to visual stimuli having luminances so low that they can stimulate rods only and appear achromatic.

Simultaneous color contrast: A perceptual effect where the color appearance of a stimulus shifts toward its background's complementary color.

Standard photometric observer: An idealized observer whose sensitivity to luminous flux as a function of wavelength matches a weighting function that has been agreed upon internationally. The CIE 1924 photopic luminous efficiency function (V_λ) is used most commonly. The CIE 1951 relative luminous efficiency function for young eyes (V'_λ) is used preferably for photopic luminances below 0.001 cd/m^2 , which are referred to commonly as *scotopic*.

Stroke width: The spatial width of dots or lines used to draw text, symbols, or icons on a visual display, expressed preferably in mm in most cases.

Temporal modulation: Changing something as a function of time, such as varying brightness at regular intervals to create the perception called *flashing*.

Tritan: A color-vision deficient person whose S cones are either absent (tritanopia) or have abnormal spectral sensitivity (tritanomaly), thereby degrading their perception of blue colors and discrimination between blue and yellow colors.

Visual angle: The angle a viewed object subtends at the eye, measured usually in degrees or minutes of arc (arcmin).

4 GENERAL REQUIREMENTS

4.1 Acceptable uses for color on visual displays

Color may be used on visual displays to aid operator performance in the following ways (ANSI-HFES-200, 2008; DISA, 1996; FAA-HF-STD-001B, 2016; NASA HIDH, 2014; NUREG-0700, 2002; SAE ARP4032B, 2013):

1. Convey meaning
2. Group information
3. Reduce visual complexity
4. Reduce visual clutter
5. Guide the operator's attention
6. Facilitate visual search
7. Signal a state
8. Show relationships
9. Identify and classify information
10. Indicate changes in status
11. Enhance legibility

Xing (2006a, 2006b, 2007) described site observations she performed at several ATC towers, terminal radar approach centers, and en route traffic control centers. She abstracted most uses listed above into three categories: (1) attention; (2) identification; and (3) segmentation.

4.1.1 Attention

ATC displays use color sometimes to attract the operator's attention and guide visual search for targets, taking advantage of the *pop-out* effect (Treisman & Gelade, 1980). Pop-out refers to a user's perception that the target(s) of interest are obvious, despite the presence of non-targets (i.e., distractors) that would slow the search, otherwise. For pop-out to occur, the target's color must differ enough from the distractors' colors to capture attention, regardless of target location. Figure 4.1.1-1 provides an illustration, in which the letters *L* become progressively easier to spot in Panels (a) through (d).

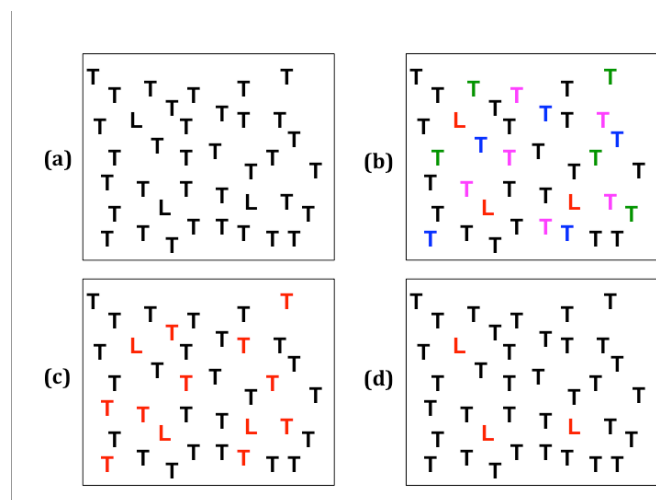


FIGURE 4.1.1-1. Pop-out effect illustration.

4.1.2 Identification

ATC displays use color sometimes to communicate data when they are presented dynamically, intermingled, or distributed irregularly on the display. In this case, colors are associated with specific meanings and the operators must understand those meanings in advance. This use of color is known more commonly as *color coding*, which can take four forms, depending on the level of measurement associated with the data the colors portray.

4.1.2.1 Nominal color coding

Nominal color coding can be used to distinguish data categories that differ importantly but cannot be arranged in rank order. For example, airplanes and helicopters might be coded using two different colors, but one is not “greater than” or “more important” than the other; consequently, the choice of colors can be arbitrary, but the colors should be readily discriminable and recognizable. Text, symbols, and icons that are drawn using the colors should be legible.

4.1.2.2 Ordinal color coding

Ordinal color coding can be used when the data can be rank ordered, but the differences among them cannot be quantified. The colors used to communicate ATC alert levels (i.e., green, yellow, orange, and red) are a familiar example in which hue is used to denote the alert’s degree of severity. Colors used for ordinal color coding should fall along a perceptual continuum that is intuitively clear to the viewer and be readily discriminable and recognizable. Text, symbols, and icons that are drawn using the colors should be legible.

4.1.2.3 Interval color coding

Interval color coding can be used when differences among the data can be quantified, but their ratios are meaningless. For example, color in images produced by a thermal camera system may vary continuously with object temperature measured in degrees Fahrenheit or Celsius, as illustrated in Figure 4.1.2.3-1, but one cannot say that one object is “twice as hot” as another.

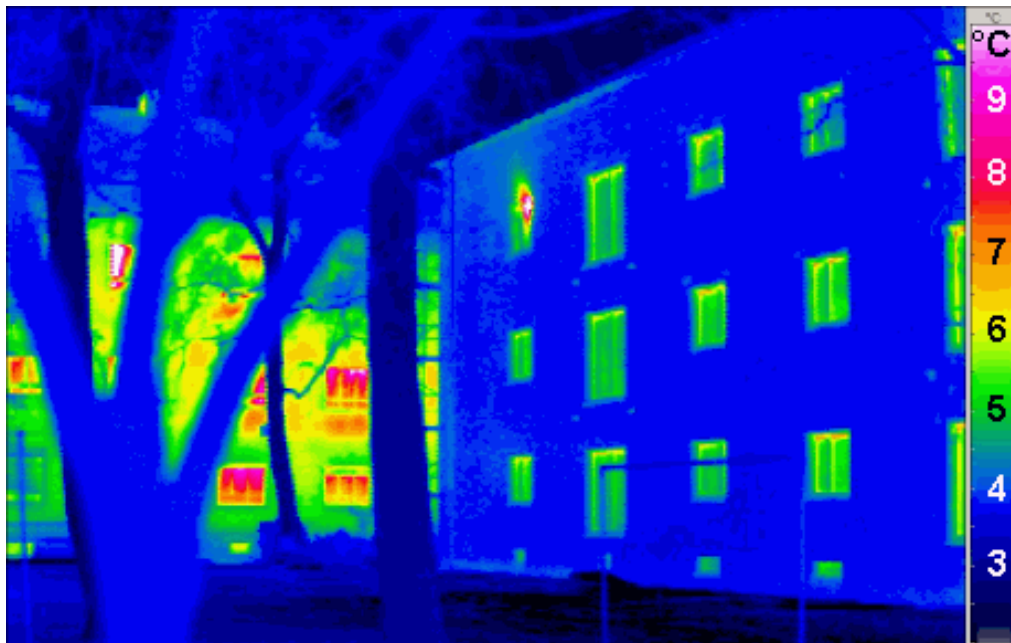


FIGURE 4.1.2.3-1. Interval color coding, as used in a thermal image.

Precipitation representations that group amounts of radar reflectivity (Z), measured on a decibel scale known as dBZ , into discrete severity levels are another example of ordinal color-coding, illustrated in Figure 4.1.2.3-2.

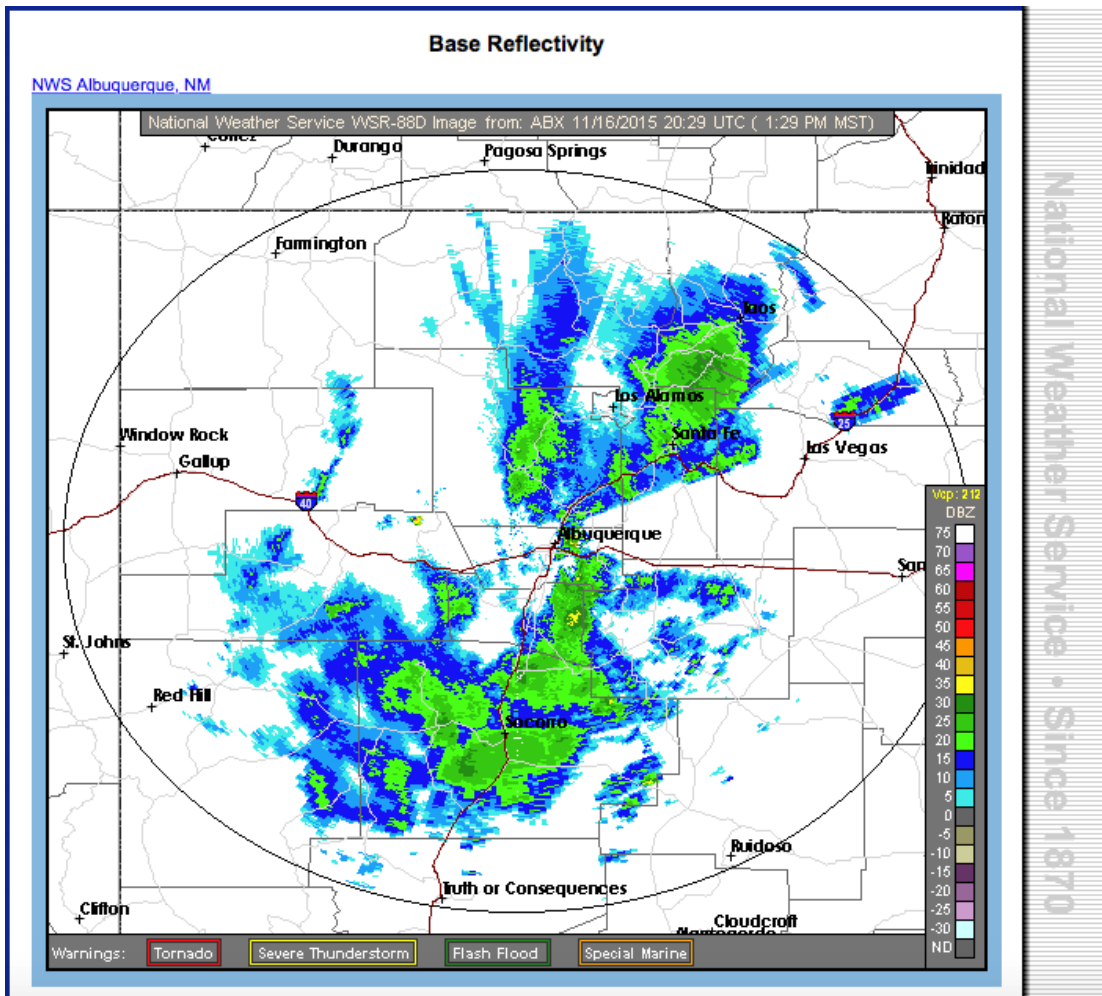


FIGURE 4.1.2.3-2. Interval color coding, as used on a weather display to show dBZ .

The practice of mapping data from one continuous variable onto varying hues (and varying saturations and/or brightnesses, possibly) is called *pseudocoloring*.³ The use of mappings that group adjacent levels of a continuous variable into ordinal-, interval-, or ratio-scale sequences and depict all members of each group identically is called *density slicing*. Figure 4.1.2.3-1, thus, illustrates ordinary pseudocolor, whereas Figure 4.1.2.3-2 illustrates density-sliced pseudocolor.

Colors used for interval color-coding should span an intuitively clear perceptual continuum but do not necessarily need to all be readily discriminable and recognizable (compare Figures 4.1.2.3-1 vs. 4.1.2.3-2, for example). Text, symbols, and icons that are drawn using the colors should be legible.

³ There are also techniques (called *false coloring*) that map two or three continuous variables onto color, but none are used on ATC displays presently.

4.1.2.4 Ratio color coding

Ratio color coding can be used when the data are quantified on a scale that has a true zero. Figure 4.1.2.4-1 provides an illustration, in which the dimmer yellow lines show progressively older aircraft positions at equal time delays from the current position, which shows delay = 0. Here, too, the colors should span an intuitively clear perceptual continuum but do not necessarily need to all be readily discriminable and recognizable. Text, symbols, and icons that are drawn using the colors should be legible.

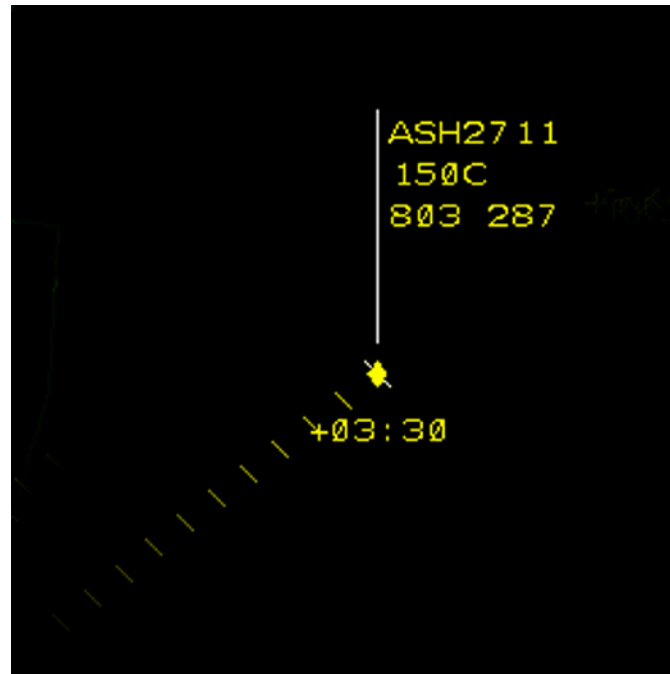


FIGURE 4.1.2.4-1. Ratio color coding, as used on ERAM to show history trails.

4.1.3 Segmentation

ATC displays use color sometimes to segment complex scenes into distinct groups of visual objects, based on a shared visual characteristic. In this application, a color is not associated necessarily with a meaning. It is used instead to group, integrate, or differentiate data. Effective use of color for segmentation requires that data displayed in the same color appear separate from other data, so operators will know where to look for related information.

Segmentation can be categorized as being either *regional* or *pattern* (Xing, 2006a, 2006b, 2007; Freidman-Berg, Allendoerfer, & Pai, 2008). Regional segmentation refers to using color to group and segregate a spatially continuous region from its surroundings. Examples of regional segmentation include using colored lines or areas to depict the locations of weather patterns, special use airspaces, or sector boundaries, as illustrated in Figure 4.1.3-1 (the green lines are sector boundaries).

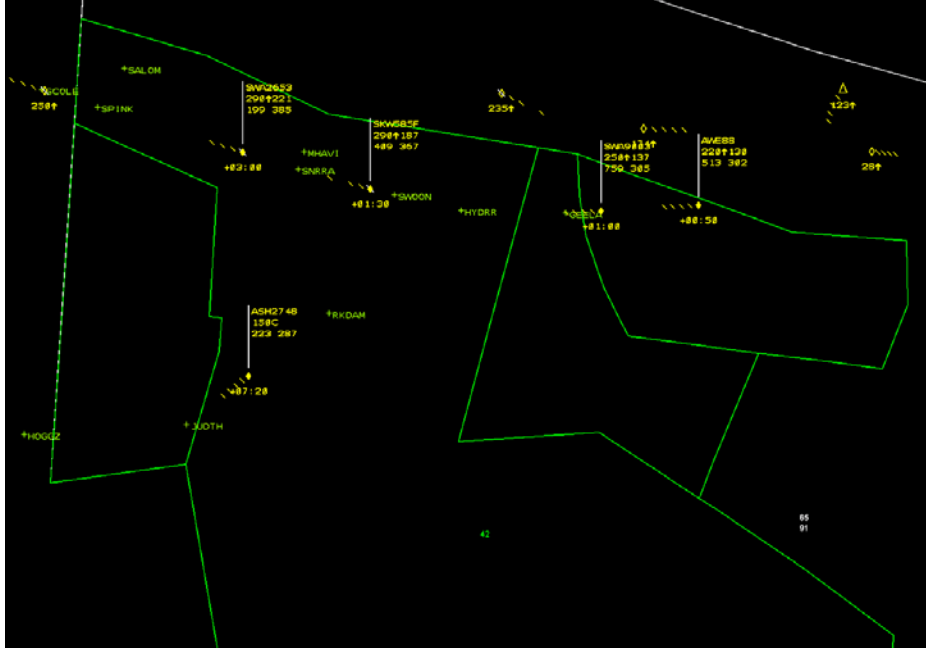


FIGURE 4.1.3-1. Regional segmentation, as used on ERAM to show sector boundaries.

Pattern segmentation refers to using color to group spatially discontinuous objects (e.g., text, symbols, or icons) into one group, separating that group from its surroundings. An example of pattern segmentation is coding data blocks for owned aircraft one color and un-owned aircraft another color, as illustrated in Figure 4.1.3-2. The owned aircraft may be interspersed among un-owned aircraft on the display, but are identifiable by their consistent data-block color.



FIGURE 4.1.3-2. Pattern segmentation, as used on STARS to distinguish owned aircraft (white) from others (green).

4.2 Color code critical information redundantly

Color *shall not* be the sole means used to code critical ATC information because some ATC operators have medically cleared color-vision defects (roughly 0.6% of the FAA population as of 2006, per T. R. Chidester and C. A. Manning, personal communications, October 28 and November 16, 2015) that may impede or prevent accurate conveyance of the information. For coding critical information, color *shall* be used redundantly with at least one other coding dimension that is independent of the operator's color vision, such as size, shape, pattern, text content, position, or temporal modulation (ANSI-HFES-100, 2007; ANSI-HFES-200, 2008; DISA, 1996; FAA-HF-STD-001B, 2016; FAA-HF-STD-003, 2009; FAA-HF-STD-009, 2015; FAA JO 7210.3Z; ISO 9241-125, 2017; ISO 9241-303, 2011; MIL-STD-1472G, 2012; NASA-STD-3001, 2011; NASA HIDH, 2014; NUREG-0700, 2002; SAE AS8034B, 2011; SAE ARP4032B, 2013). Auditory signals are used redundantly sometimes with visual alerts (FAA-HF-STD-001B, 2016; FAA-HF-STD-003, 2009; FAA-HF-STD-008, 2014).

4.2.1 Redundant coding illustrations

Figures 4.2.1-1 through 4.2.1-3 illustrate color coding used redundantly with shape, size, and pattern coding, respectively.





Hostile	Friendly	Neutral	Unknown
			

FIGURE 4.2.1-1. Redundant coding using color and shape.

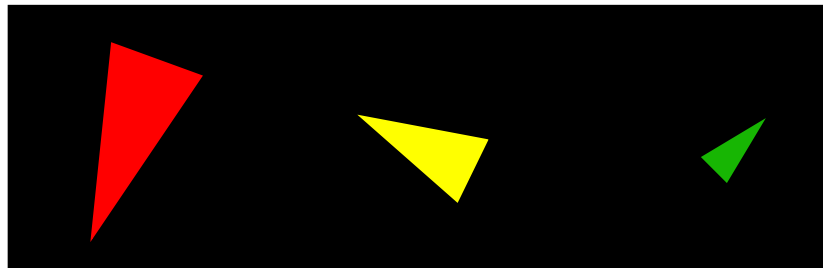


FIGURE 4.2.1-2. Redundant coding using color and size.

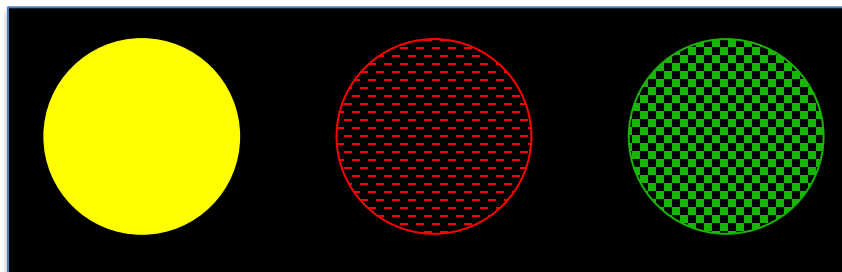


FIGURE 4.2.1-3. Redundant coding using color and pattern.

Figures 4.2.1-4 through 4.2.1-7 are more complex illustrations of redundant coding. Figure 4.2.1-4 shows color coding used redundantly with shape, position, and temporal-modulation coding to signal an alarm. In this example, the diamond flashes, initially. Once the operator acknowledges the alarm, the flashing ceases and the diamond may be removed, or it may remain to increase the alarm’s conspicuity and thereby reduce the operator’s visual-search time for relocating it, later.

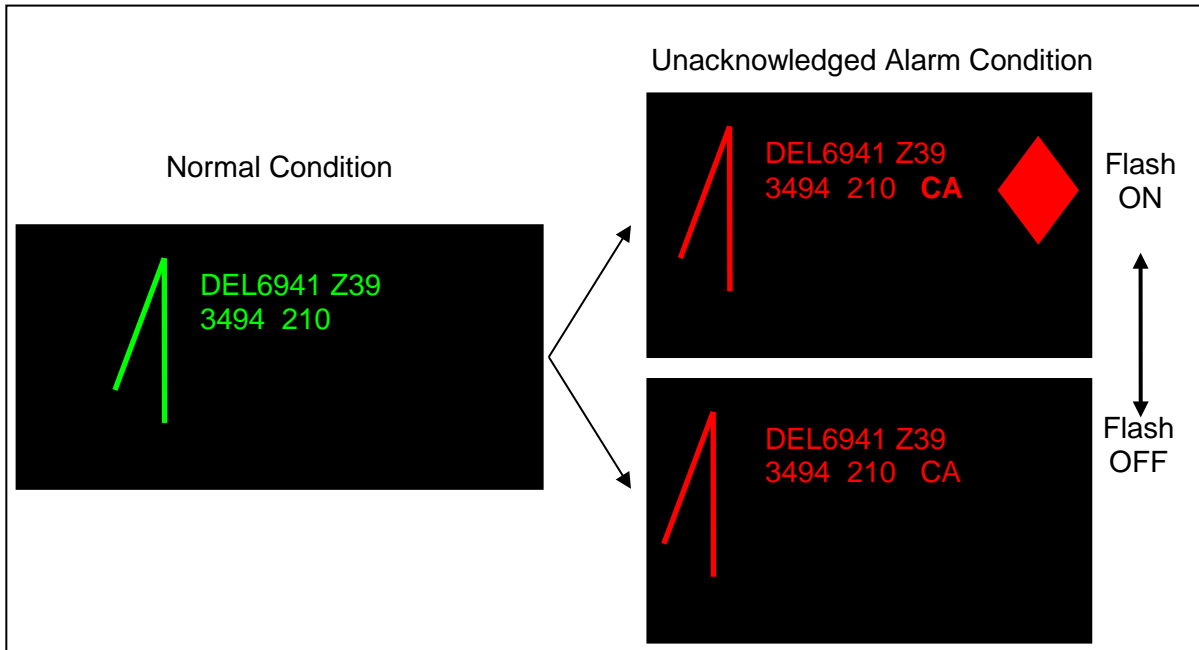


FIGURE 4.2.1-4. Redundant coding using color, shape, position, and temporal modulation.

Figure 4.2.1-5 (from Chidester et al., 2011) shows how STARS uses color coding redundantly with text content, position, and temporal modulation coding to convey an unacknowledged alarm: The red letters “CA” have been added at the upper left of three data blocks and flash.

Owned Aircraft	Unowned Aircraft	Pointout Aircraft	Owned Alert Aircraft	Unowned Alert Aircraft	Pointout Alert Aircraft
AAL8960 Z08 3113 climb 23 Y945 310	CAAC8436 Z15 4319 desc 39 U779 290	DEL3440 Z15 PD 2191 desc 23 L368 350	CA CAD1363 Z46 5193 desc 48 E246 280	CA CAAC9498 ZXU 2535 [100] 36 V388 310	CA CAC1672 Z08 PD 2191 desc 23 T134 60

FIGURE 4.2.1-5. Redundant STARS coding using color, text content, position, and temporal modulation.

Figure 4.2.1-6 illustrates color coding used redundantly with shape and position coding. The purpose in this case is to convey an aircraft's track history. The oldest track is the blue diamond furthest from the aircraft symbol and associated data block.



FIGURE 4.2.1-6. Redundant coding using color, shape, and position.

Figure 4.2.1-7 goes a step further by adding size coding for the track-history's age. The oldest track is furthest from the aircraft symbol and data block, and is the smallest blue diamond.



FIGURE 4.2.1-7. Redundant coding using color, shape, position, and size.

4.2.2 Don't use brightness coding as a redundant coding dimension

Adding brightness coding to a purely chromatic color code is not always a reliable way to provide redundancy because protans may not recognize brightness differences that are apparent to others and may see differences that people with normal color vision (NCV) do not. Further, use of a purely chromatic code reduces the number of colors that can be used to communicate with NCV operators. (The number of usable colors is discussed in [Section 5.9](#).) Consequently, brightness coding *shall not* be used to add a redundant coding dimension to chromaticity. Instead, all three of color's perceptual dimensions (i.e., brightness, hue, and saturation) should be used to make the colors in a color code as distinctive and recognition as possible.

4.3 Use color purposefully

Color differences *shall not* be introduced solely for aesthetic, stylistic, or decorative purposes because unnecessary color proliferation can increase visual search times, degrade legibility, cause operators to infer unintended meanings or groupings, and make the display appear

cluttered. Color differences *shall* be used only when they can be expected to improve operator performance (ANSI-HFES-200, 2008; DISA, 1996; FAA-HF-STD-001B, 2016; FAA-HF-STD-003, 2009; FAA-HF-STD-008, 2014; FAA-HF-STD-009, 2015; FAA JO 7210.3Z; ISO 9241-125, 2017; NASA HIDH, 2014; NUREG-0700, 2002; SAE ARP4032B, 2013).

4.4 Use color-code meanings consistently

Consistency in user interfaces promotes learning new interfaces and reduces user error; therefore, color-code meanings *shall* be consistent within a screen, within a system, and across related systems that are used by the same operators. The meanings *shall* be fixed and not change over time. Ideally, color-code meanings should become consistent across all ATC systems eventually (ANSI-HFES-200, 2008; DISA, 1996; FAA-HF-STD-001B, 2016; FAA-HF-STD-003, 2009; FAA-HF-STD-008, 2014; FAA-HF-STD-009, 2015; FAA JO 7210.3Z; ISO 9241-125, 2017; ISO 9241-303, 2011; MIL-STD-1472G, 2012; NASA HIDH, 2014; NUREG-0700, 2002; SAE ARP4032B, 2013). See [Section 5.2](#) for ATC color-code meaning requirements.

4.5 Maintain consistent color appearance

A color's appearance is affected by its background — an effect known as *simultaneous color contrast* and illustrated in Figure 4.5-1. Specifically, the foreground color's appearance shifts toward the background's complementary color. The effect is most pronounced when the background color is highly saturated and its luminance is similar to the foreground luminance. (If the background's luminance is vastly greater than the foreground's (e.g., 50 times more), it may be difficult for viewers to discern the foreground color at all.)

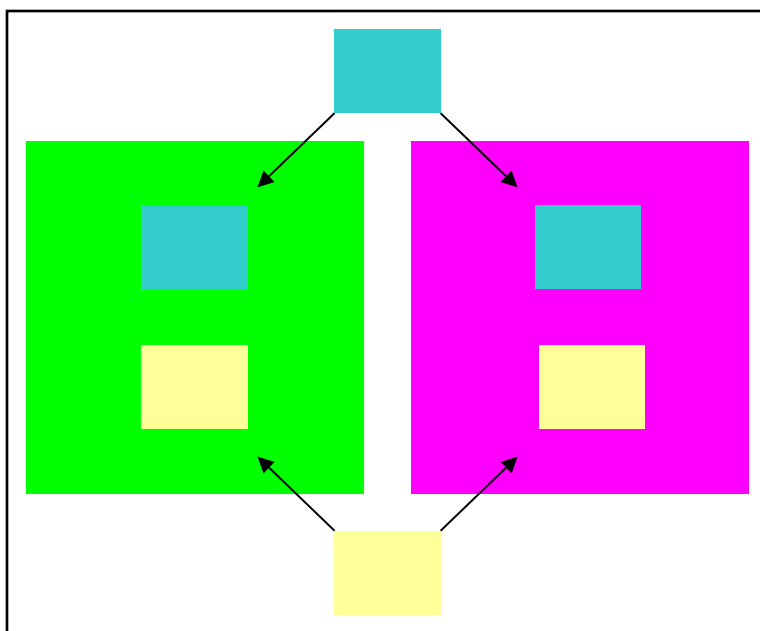
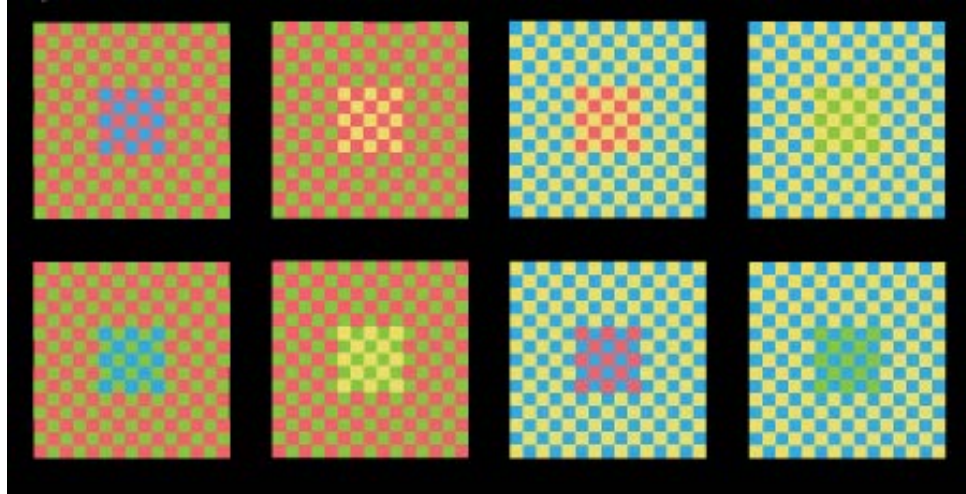


FIGURE 4.5-1. Simultaneous color-contrast illustration.

An opposite effect can occur, where the foreground and background colors shift toward each other — an effect known as *color assimilation* and illustrated in Figure 4.5-2. This effect is seen less often because it is most likely when the foreground is a pattern containing repetitive high spatial frequencies, which is an unusual visual stimulus in most applications.



NOTE: From Stockman, A., & Brainard, D. H. (2009). Color vision mechanisms. In M. Bass, C. DeCusatis, J. Enoch, V. Lakshminarayanan, G. Li, C. Macdonald, V. Mahajan & E. van Stryland (Eds.), *The Optical Society of America Handbook of Optics*, 3rd ed., Volume III: Vision and Vision Optics, Copyright 2009, with permission from McGraw-Hill Education.

FIGURE 4.5-2. Color assimilation illustration.

Predicting color-appearance changes caused by background color can be difficult; further, if the background can change over time (as is the case for ATC weather depictions, for example), it may be impractical to alter the foreground's standard red, green, and blue (sRGB) values dynamically in software to compensate. Figure 4.5-3 shows how a weather depiction might cause unintended color-appearance changes, as well as legibility problems.

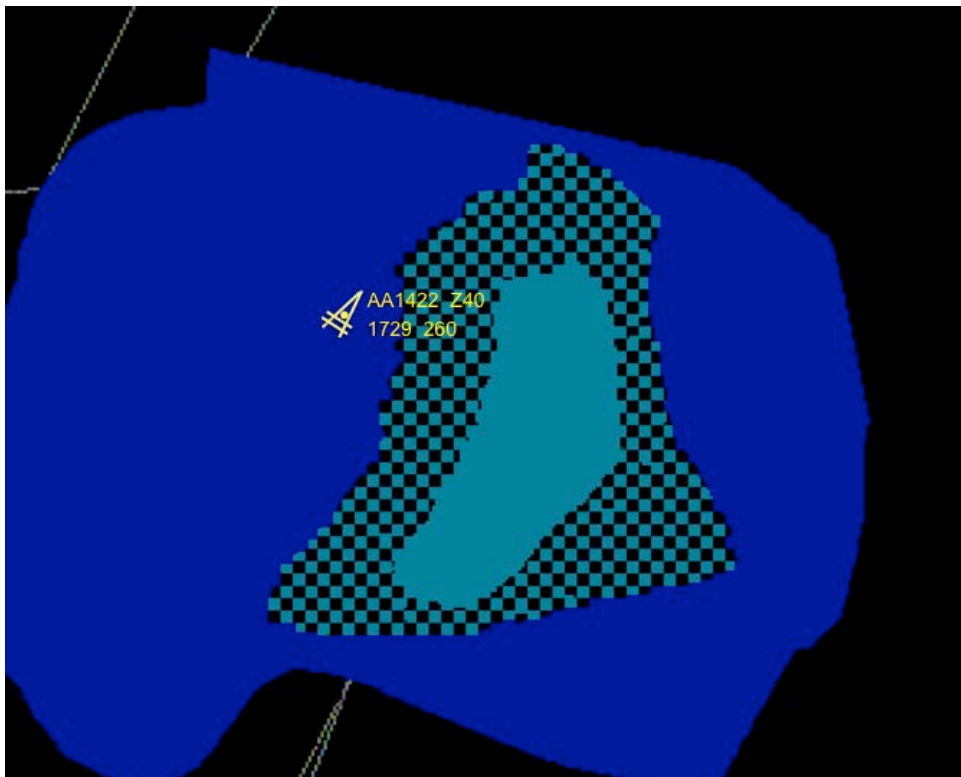


FIGURE 4.5-3. A potentially troublesome weather depiction.

To avoid or reduce color-appearance inconsistencies caused by background changes or differences, achromatic colors *shall* be used for backgrounds, ordinarily. If a solid color background must be used temporarily, it *shall* have low saturation and luminance equal or close to the normal background's. More background color-requirements appear in [Section 5.4](#).

An alternative to solid colors that may be useful for ATC weather depictions is to use sparse spatial patterns, such as the two illustrated in Figure 4.5-4. Sparse patterns are less apt to cause color-appearance inconsistencies, as well as legibility problems, for superimposed text, symbols, and icons.

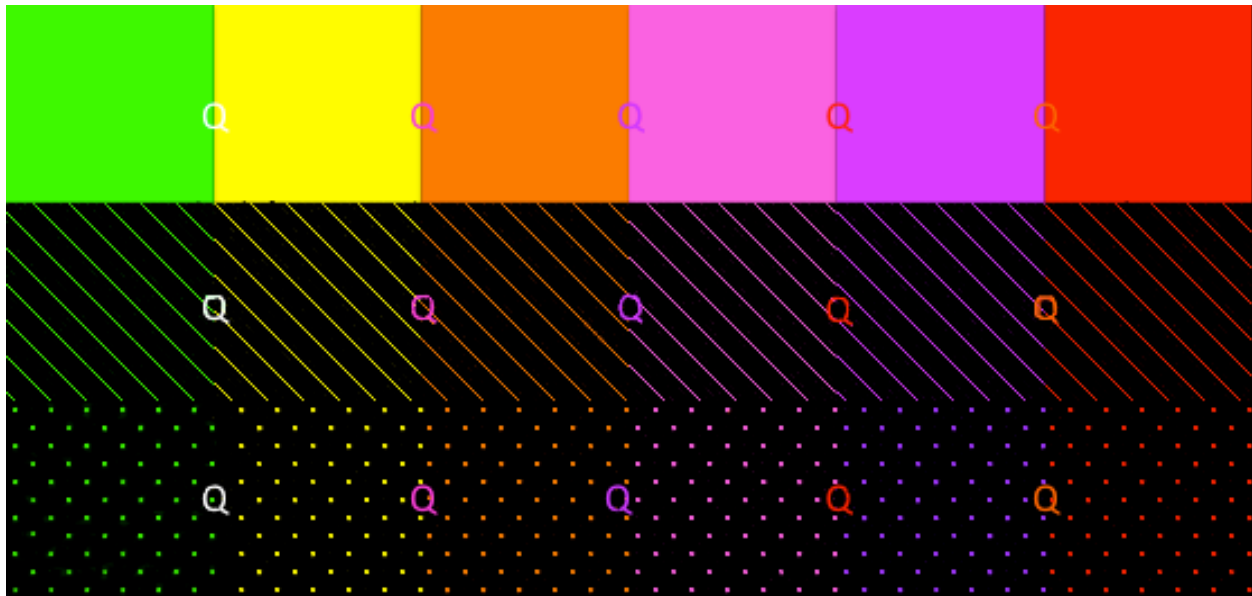


FIGURE 4.5-4. Stimulus color and legibility on solid, striped, and stippled backgrounds.

4.6 Don't create chromostereopsis

Placing highly saturated colors having hues that differ widely in the color spectrum in close spatial proximity on a black or dark background can make them appear to lie in different depth planes. This effect, known as *chromostereopsis*, is especially obvious for the red produced by setting a typical display's sRGB values = $(n, 0, 0)$, combined with the blue produced by sRGB = $(0, 0, n)$, where n is at or near 255. Figure 4.6-1 shows an example. The effect is caused by physiological characteristics of the eye, rather than neuronal processing. Its perceived magnitude varies widely among viewers, so creating chromostereopsis unintentionally or deliberately in an attempt to use it as a design feature *shall* be avoided. Figure 4.6.2 shows that chromostereopsis (and trouble reading blue text) is eliminated or reduced greatly on a medium gray background.

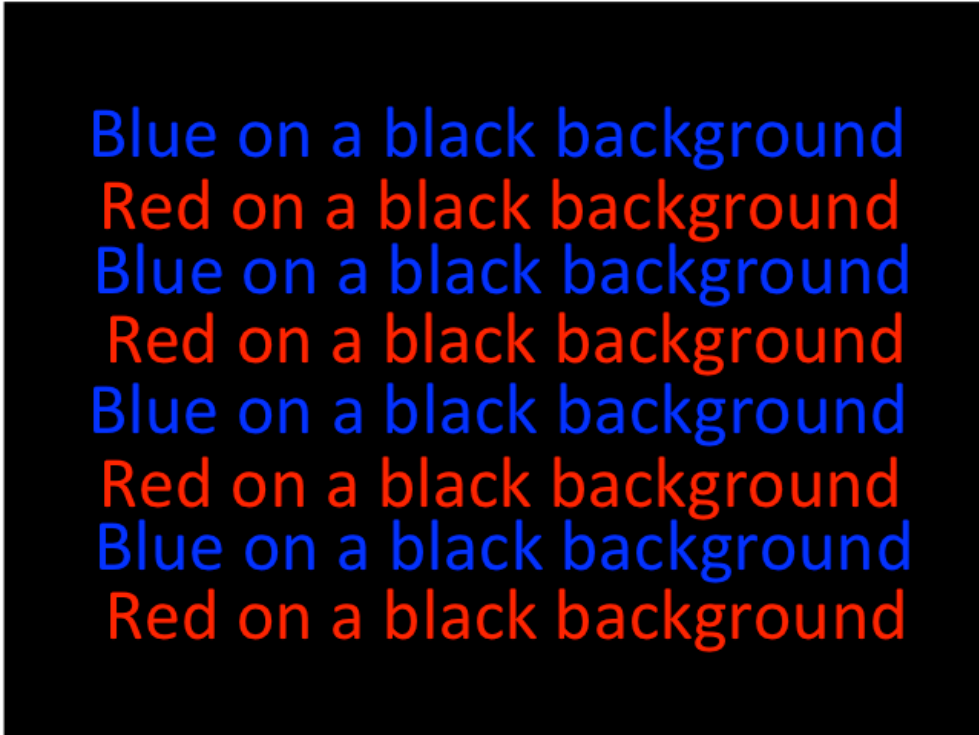


FIGURE 4.6-1. Chromostereopsis illustration.

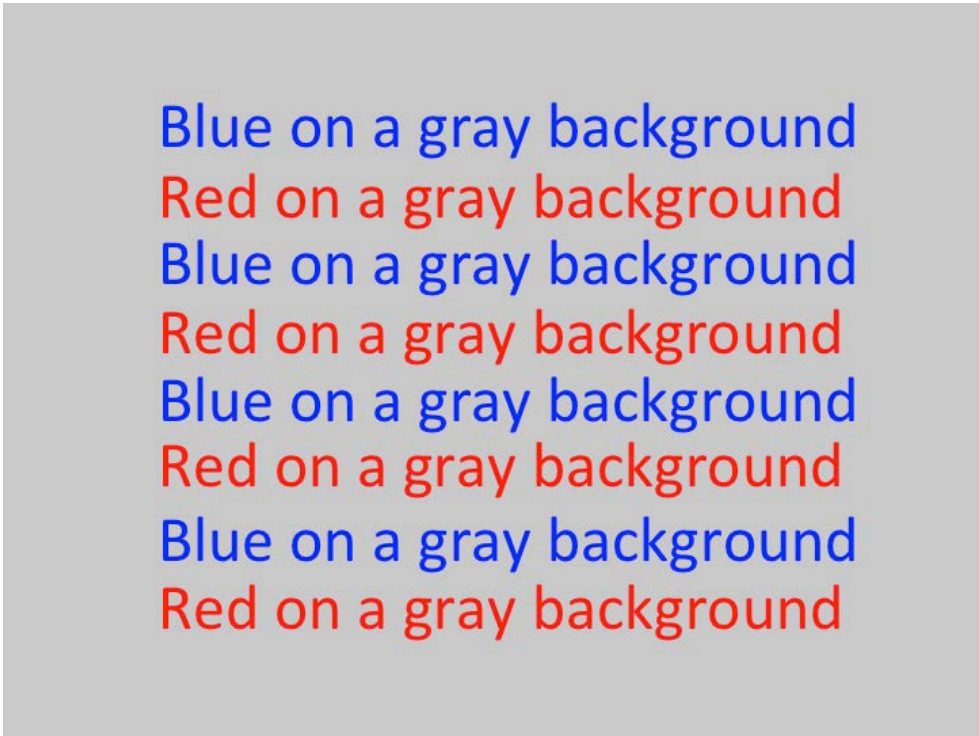


FIGURE 4.6-2. Effects of a gray background on chromostereopsis and legibility of blue.

4.7 Don't make color hard to discern due to small stimulus size

Color discrimination and recognition become progressively more difficult as the angle the stimulus subtends at the viewer's eye shrinks below 1 degree or so; specifically, it tends to appear less saturated, relative to larger stimuli. This effect is illustrated in Figure 4.7-1. It is more pronounced for colors that stimulate short-wavelength-sensitive cones (S cones) preferentially (e.g., blues and mixtures that include blue as a major component, such as cyan and purple) and is known commonly therefore as *small-field tritanopia*. The stimulus-height requirements in [Section 5.6](#) help to mitigate problems of this type.

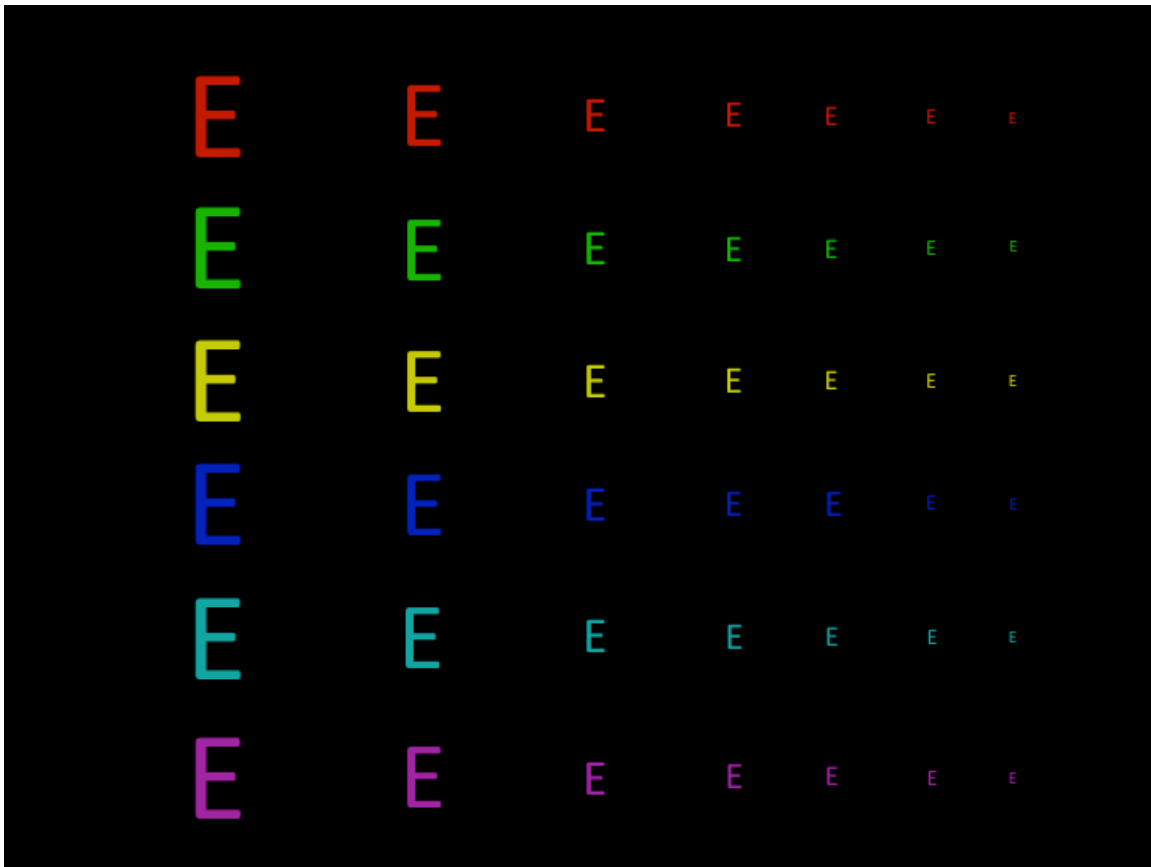


FIGURE 4.7-1. Effects of stimulus size on color appearance.

4.8 Don't require accurate peripheral color discrimination and recognition

Ordinarily, one can assume the viewer is looking at a stimulus directly. This means it is imaged on the fovea, where color vision is operative fully. Stimuli presented outside the fovea tend to appear less saturated and their brightnesses change. These effects result from the presence of a yellowish macular pigment in the central 5 to 10 degrees of the visual field (there are individual differences) and increases in the human visual system's red, green, yellow, and blue receptive-field sizes that occur with increasing stimulus eccentricity. Yellow vs. blue discrimination tends to remain more robust than red vs. green discrimination as a stimulus' retinal eccentricity increases. See CIE 15:2014 and Post (1992, pp. 145-146) for further information.

The public's move to high-definition television, with its accompanying 16:9 wide aspect ratio, has exacerbated the potential for ATC operators to have problems seeing peripheral colors accurately, compared to the older, 4:3 aspect-ratio convention. This situation has arisen because of an understandable FAA desire to reduce costs by using commercial off-the-shelf (COTS) displays. Given typical ATC-operator viewing distances, it is therefore increasingly likely that ATC applications will present color stimuli further in the periphery than has been the case in the past.

If a need for accurate peripheral color discrimination or recognition is unavoidable, make the stimuli as large, bright, and saturated as is feasible. It is better, though, to use an attention-getting visual cue, accompanied perhaps by an auditory cue, to draw attention and cause the operator to view the stimuli foveally. Temporal modulation is an especially good visual cue for drawing attention to peripheral stimuli.

4.9 Acceptable ways to use temporal modulation of color

Flashing a stimulus on and off at regular intervals is a type of temporal color modulation that is used often to draw an operator's attention to newly important items on a display, especially for the purpose of signaling alerts. It is not permissible for text, however, because it can compromise the text's legibility. Text *shall not* flash on and off, to ensure its legibility is maintained at all times.

Flashing a stimulus by alternating between its normal luminance and one that is obviously brighter is an acceptable method for drawing attention to text, as well as other displayed items. This type of flashing maintains legibility by ensuring the item's luminance contrast against its background never falls below normal.

Another attention-getting type of temporal modulation that is acceptable for text and other displayed items is to alternate the item's color with its background's—a technique that is termed *polarity reversal* or *inverse video*, frequently. This method maintains legibility by keeping the item's luminance contrast against its background constant.

Attention may also be drawn to displayed items by adding a temporally modulated marker (e.g., an underline or symbol) nearby.

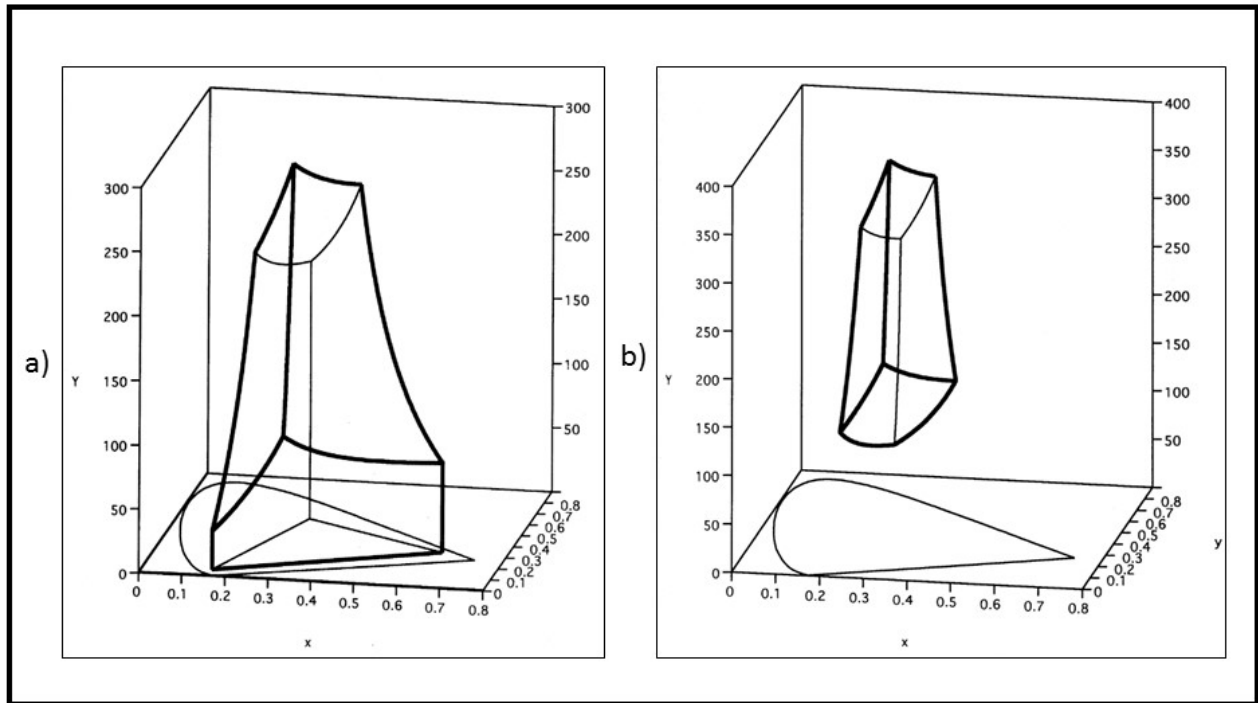
The FAA has requirements regarding the use of temporal modulation that address parameters such as duty cycle and frequency. FAA HF-STD-001B (2016), FAA HF-STD-003 (2009), and FAA HF-STD-008 (2014) should be consulted for further information.

4.10 Consider the viewing environment's ambient illumination

Ambient illumination falling on a display screen can reflect into the operator's eyes, causing glare. Specular glare produces an image, such as the operator's shirt or another object in the operator's vicinity. It is more apt to be seen in the glossy screens that have become common to COTS displays. Diffuse glare comes usually from overhead lights, windows, or other sources that are too far off-axis to reflect an image directly into the operator's eyes, although matte screens can diffuse glare that would be specular, otherwise. Both types of glare mix with light

emitted by the display and thereby reduce the display's effective luminance contrast and range of chromaticity coordinates it can present, thereby reducing the display's effective color gamut. Display screens have anti-reflection treatments typically, to reduce glare.

The effect of ambient illumination on an electronic display's color gamut can be calculated and depicted graphically. Figure 4.10-1 shows an example, in which Panel (a) shows a hypothetical display's color gamut for zero ambient illumination and Panel (b) shows the gamut with 100 candelas per square meter (cd/m^2) of luminance reflecting off the screen. The thick, dark lines are in front and closest to the viewer; the thin lines are behind.



NOTE: From Post, D. L., & Lloyd, C. J. C. (1994). Colour display gamuts and ambient illumination. *Displays*, 15, pp. 41 & 43, with permission from Elsevier.

FIGURE 4.10-1. Effects of ambient illumination on an electronic display's color gamut.

Problems caused by ambient illumination can be severe in towers because towers have windows that admit sunlight during daytime. Wilson, Wilson, and Jha (2007) measured display illuminances at 15 US towers and reported a peak daytime value of roughly 55,200 lumens per square meter (lux) during operational conditions. Terminal, en route, and oceanic facilities have no windows and their ambient illumination is much lower.

NOTE:

Illuminances in en route facilities. Informal measurements were taken in 2014 at radar-controller display surfaces in FAA en route facilities in Washington (ZDC) near midnight and Memphis (ZME) near 2 a.m. (These facilities were said to use relatively high lighting levels late at night and early in the morning by a few people who were familiar with them and other en route

facilities.) The values obtained range from 0.3 to 25.5 lux and average 10 lux; the upper end of the 99% confidence interval is 38 lux (E. A. Sierra, personal communications, January 28 and February 19, 2014). These values are consistent with the 3.1- to 23.3-lux range reported for work surfaces in en route facilities by Krois et al. (1991).

4.11 Avoid large mismatches between display and environmental luminances

Large differences between the display's luminance and that of reflecting objects the operator must see in the immediate work environment (e.g., paper manuals, notes, and maps) should be avoided. The operator will light-adapt to whichever is greater, which can make the others hard to see. In extreme cases, the operator may see disturbing afterimages when looking away from brighter stimuli.

The luminance-contrast ratio (defined herein as the ratio of one luminance to a lesser one) between the two aforementioned luminances *shall not* exceed 3:1. The environmental luminance used to calculate this ratio *shall* be that of the most luminous object in the operator's immediate work environment. The display luminance used to calculate the ratio *shall* be that of the most luminous stimulus used on the display (ANSI-HFES-100, 2007; ANSI/IES RP-1-12, 2012; FAA-HF-STD-001B, 2016; MIL-HDBK-759C, 1995; MIL-STD-1472G, 2012; NASA HIDH, 2014; NUREG-0700, 2002).

NOTE:

Example: Taking 88% as an estimate of typical office paper's reflectance (see <http://www.paperonweb.com/paperpro.htm#Optical%20Properties>), 38 lux of ambient illumination will produce roughly $(38 \text{ lux} * 0.88 / \pi =)$ 10.6 cd/m² from white portions of paper manuals, etc. The 3:1 ratio limit implies, then, that the displays at ZDC and ZME should be adjusted to produce a peak white luminance no greater than $(10.6 \text{ cd/m}^2 * 3 =)$ 32 cd/m² if we assume that the illuminances on the paper manuals, etc. match those that were measured at the display surfaces in 2014 (see the Section 4.10 Note) and the display luminance is used as the numerator.

5 DETAILED REQUIREMENTS

5.1 Color requirements unique to terminal systems

FAA JO 7210.3Z Chapter 3 Section 9 mandates certain colors and usage rules for most terminal ATC systems. Those mandates *shall* apply to all ATC systems subject to them; nothing in this standard may be taken to supersede them. See related Note in [Section 2.4](#).

5.2 Use the standard meanings for common ATC colors

Color-code meanings *shall* be consistent with the following ATC operator population stereotypes, which pertain mostly to alert levels (FAA-HF-STD-001B, 2016; FAA-HF-STD-003, 2009; FAA-HF-STD-008, 2014; FAA-HF-STD-009, 2015):

- a. Flashing red *shall* be used only to signal an unacknowledged alarm, signaling an emergency that requires immediate action.
- b. Red *shall* be used to signal an acknowledged alarm, signaling an emergency that requires immediate action.
- c. Orange or amber *shall* be used to signal an alert, signaling an unusual condition that requires immediate attention but not immediate action.
- d. Yellow *shall* be used to signal a caution, signaling an unusual condition that requires neither immediate attention nor immediate action.
- e. Green *shall* be used to signal that it is OK to proceed, normal, satisfactory, or within-tolerance status.
- f. White *shall* indicate alternative functions or system conditions that do not have operability or safety implications.
- g. Blue *shall* be used only for advisory or informational items.
- h. Gray should be used for items the operator can ignore because they are unmonitored, unmanaged, inactive, out of service for a long term, or taken offline intentionally.

5.3 Provide ability to display a key for non-stereotypical color-coding sets

ATC operators may be able to discriminate and recognize all members of large, well-chosen color-coding sets reliably, but they may not always recall the colors' meanings immediately. Consequently, if a color-coding set includes colors other than the ATC user population stereotypes listed in Section 5.2, a capability to display a key temporarily that shows the entire set and defines each color's meaning *shall* be provided to refresh the operator's memory (DISA, 1996; FAA-HF-STD-001B, 2016; FAA-HF-STD-003, 2009; FAA-HF-STD-008, 2014; FAA-HF-STD-009, 2015).

5.4 Use black or gray as the background color

The display background on which ATC information is presented *shall* be either black or gray. These choices simplify the task of choosing sRGB values that produce desired color appearances by reducing the chances of producing unintended changes in foreground-color appearance, as discussed in [Section 4.5](#) (ANSI-HFES-100, 2007; ANSI-HFES-200, 2008; ISO 9241-303, 2011; NUREG-0700, 2002).

5.4.1 Use a black background for low ambient-illumination conditions

Black (i.e., sRGB = (0, 0, 0)) should be used for the low ambient-illumination conditions (i.e., less than 200 lux at work surfaces) common to terminal, en route, and oceanic settings, and tower settings at night, because it helps preserve dark adaptation and provides the maximum range of luminance contrasts the display can produce (FAA JO 7210.3Z; Friedman-Berg, Allendoerfer, & Pai, 2008; MIL-HDBK-759C, 1995).

5.4.2 Use a gray background for normal or high ambient-illumination conditions

Gray⁴ backgrounds should be used for settings that use normal office-lighting illumination levels (i.e., 200 lux or more at work surfaces; ANSI/IES RP-1-12, 2012; ANSI-HFES-100, 2007) and during daytime for tower settings (DISA, 1996; MIL-HDBK-759C, 1995; NUREG-0700, 2002). Gray reduces the visibility of glare from the display surface, which is most apt to be problematic in bright ambient-lighting conditions. Gray backgrounds having a luminance that is intermediate to those of foreground colors yield better foreground-color recognition than black or white backgrounds (Carter & Carter, 1988; Carter, 1997; Jacobsen, 1986).

5.5 Luminance-contrast requirements for text, symbols, and icons

To ensure legibility, the luminance-contrast ratio between text, symbols, and icons relative to all backgrounds against which they may appear *shall* be no less than 3:1 in the presence of the highest expected ambient illumination. Larger ratios are permissible and may improve legibility (ANSI-HFES-100, 2007; ANSI-HFES-200, 2008; FAA-HF-STD-001B, 2016; FAA-HF-STD-003, 2009; FAA-HF-STD-008, 2014; MIL-HDBK-87213A, 2005; NUREG-0700, 2002).

Several standards say a 7:1 ratio should be provided. This recommendation may be especially prudent for ATC displays when weather depictions or other background items may otherwise reduce luminance-contrast ratios for superimposed text, symbols, and icons below the required 3:1 minimum temporarily (ANSI-HFES-200, 2008; FAA-HF-STD-003, 2009; FAA-HF-STD-008, 2014; NUREG-0700, 2002).

NOTE:

Demonstrating compliance: Assessing whether the contrast-ratio requirement is met for text, symbols, and icons requires calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the Intracharacter Luminance and Contrast test described in Information Display Measurements Standard (IDMS) 1.0.3. This assessment is performed for each color used on the display against all backgrounds on which those colors may appear, using a grille spacing that represents the stroke-width and character spacing of the smallest font used to portray information on the display. The highest ambient illumination

⁴ Even very low-luminance achromatic colors tend to appear white, rather than gray, unless the observer is light-adapted to a more luminous stimulus. (Consider the appearance of stars at night.) That is, gray can be perceived only in relation to something brighter, ordinarily. This means there are no specific sRGB values that ensure a background will look gray. In most situations, the viewing environment must include stimuli having a higher luminance than the display background to make the background look gray.

expected at the display screen is to be accounted for when assessing whether the contrast-ratio requirement is met.

5.6 Height requirements for text, symbols, and icons

The following requirements are summarized in [Table 5.6-I](#) and synthesized from ANSI-HFES-100 (2007), ANSI-HFES-200 (2008), DISA (1996), FAA-HF-STD-001B (2016), FAA-HF-STD-003 (2009), FAA-HF-STD-008 (2014), ISO 9241-303 (2011), MIL-HDBK-87213A (2005), MIL-STD-411F (1997), MIL-STD-1472G (2012), NASA-STD-3001 (2011), NASA HIDH (2014), and NUREG-0700 (2002).

5.6.1 Text or graphics embedded within symbols

To ensure legibility, if color discrimination and/or recognition are not critical to the operator's task, the height of text or graphics embedded within symbols (e.g., labels within symbols) *shall* subtend at least 10 arc-minutes (arcmin) of visual angle at the operator's expected viewing distance. If color discrimination and/or recognition are critical, the height *shall* exceed 10 arcmin.

5.6.2 Individual letters, symbols, and icons

If color discrimination and/or recognition are not critical to the operator's task, the height of letters, symbols, and icons that must be recognized individually *shall* subtend at least 20 arcmin of visual angle at the operator's expected viewing distance and not exceed 35 arcmin; 24 to 35 arcmin is preferred. If color discrimination and/or recognition are critical, the height *shall* subtend at least 30 arcmin; 45 arcmin is preferred.

5.6.3 Short text strings

5.6.3.1 Rapid reading not required

If color discrimination and/or recognition are not critical to the operator's task, the height of short text strings that need not be read rapidly *shall* subtend at least 16 arcmin of visual angle at the operator's expected viewing distance and not exceed 30 arcmin. If color discrimination and/or recognition are critical, the height *shall* subtend at least 20 arcmin and not exceed 30 arcmin.

5.6.3.2 Rapid reading required

If color discrimination and/or recognition are not critical to the operator's task, the height of short text strings that must be read rapidly *shall* subtend at least 24 arcmin of visual angle at the operator's expected viewing distance and not exceed 30 arcmin. If color discrimination and/or recognition are critical, the height *shall* exceed 24 arcmin and not exceed 30 arcmin.

5.6.4 Long text strings

If color discrimination and/or recognition are not critical to the operator's task, the height of long text strings *shall* subtend at least 16 arcmin of visual angle at the operator's expected viewing distance and not exceed 30 arcmin; 20 to 22 arcmin is preferred. If color discrimination and/or recognition are critical, the height *shall* subtend at least 20 arcmin and not exceed 30 arcmin.

TABLE 5.6-I. Height requirements for text, symbols, and icons, expressed as arcmin of visual angle subtended at the operator’s expected viewing distance.

	Color Not Critical	Color Critical
Embedded	10 minimum	>10 minimum
Individual	20 minimum	30 minimum
	24-35 preferred	45 preferred
	35 maximum	
Short text strings – not time-critical	16 minimum 30 maximum	20 minimum 30 maximum
Short text strings – time-critical	24 minimum 30 maximum	>24 minimum 30 maximum
Long text strings	16 minimum	20 minimum
	20-22 preferred	30 maximum
	30 maximum	

5.7 Minimum acceptable color difference among search targets

The magnitude of perceived differences among color-coded stimuli is affected by the angle they subtend at the viewer’s eye. To minimize search times for color-coded targets, the smallest size-corrected color difference between any two color-coded targets the operator may need to search for on an electronic display should be no less than 28 when computed:

$$\Delta E^*_{uv-sc} = ((K_L^* * \Delta L^*)^2 + (K_u^* * \Delta u^*)^2 + (K_v^* * \Delta v^*)^2)^{0.5} , \quad (1)$$

where ΔE^*_{uv-sc} is the size-corrected color difference, the coefficients K_L^* , K_u^* , and K_v^* are computed as described in [Appendix A](#), and ΔL^* , Δu^* , and Δv^* are computed in accordance with the conventions of the CIE 1976 ($L^*u^*v^*$) color space (CIELUV) described in CIE 15:2004. The highest ambient illumination expected at the display screen *shall* be accounted for when computing ΔL^* , Δu^* , and Δv^* .

When using Eqn. 1 and computing its CIELUV values, Y_n *shall* be set equal to the display’s peak-white luminance, as determined in accordance with the White-Point Accuracy test described in [Section 5.16.1.1](#) u'_n *shall* be set equal to 0.1978, and v'_n *shall* be set equal to 0.4683 (these are the CIE 1976 chromaticity coordinates of CIE standard illuminant D₆₅).

Carter (1989) estimated that $\Delta E^*_{uv-sc} \geq 28$ is needed to yield minimum visual search times for color-coded stimuli. Values less than 28 may therefore yield suboptimal search times, but this does not mean they will be unacceptably long, necessarily. Color sets that yield $\Delta E^*_{uv-sc} < 28$ for one or more color pairs should be tested using participants who are representative of the intended user population to determine whether the search times are acceptable.

NOTE:

Discussion: Readers who are familiar with minimum CIELUV color-difference requirements in other standards may wonder at the use of size correction and criterion of 28 required here. Typically, size correction is omitted and the criterion is 20. The original basis for the typical requirement (whether cited or not) is Carter (1989), which showed that a criterion equal to 20 fit the data best for a CIELUV model that omitted size correction. The main point of Carter (1989), though, was to show the value of using size correction. For that case, a better fit was obtained using the size-correction coefficients in Eqn. 1 and a criterion equal to 28. Other standards that prescribe a criterion equal to 40 instead are based on Carter and Carter (1981), which omitted size correction and involved much smaller stimuli than Carter (1989). The requirements stated above regarding Y_n , u'_n , and v'_n are those used by Carter (1989) and are required here to ensure consistent results.

5.8 Minimum acceptable difference for discriminable spatially-adjacent colors

In many applications where ordinal, interval, or ratio color-coding is used, colors are adjacent to one another. The minimum acceptable color difference among spatially adjacent colors that must be discriminable *shall* be no less than 9.9 when computed:

$$\Delta E^*_{ab} = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{0.5}, \quad (2)$$

where ΔE^*_{ab} is the color difference and ΔL^* , Δa^* , and Δb^* are computed in accordance with the conventions of the CIE 1976 ($L^*a^*b^*$) color space (CIELAB) described in CIE 15:2004. The highest ambient illumination expected at the display screen *shall* be accounted for when computing ΔL^* , Δa^* , and Δb^* .

When using Eqn. 2 and computing its CIELAB values, Y_n *shall* be set equal to the display's peak white luminance, as determined in accordance with the White-Point Accuracy test described in [Section 5.16.1.1](#), and X_n and Z_n *shall* be set equal to the corresponding CIE 1931 tristimulus values, as described in CIE 15:2004, of CIE standard illuminant D₆₅.

The 9.9 criterion required above is the maximum value Brainard (2003, p. 203) obtained after computing 95% confidence intervals for the lengths of the major and minor axes of MacAdam's (1942) ellipses in CIELAB. The 9.9 criterion is taken here to be a conservative estimate of the minimum acceptable color difference among spatially adjacent colors that must be discriminable.

5.9 Maximum permissible color-coding set size

Applying minimum color-difference requirements within bounded spaces such as those depicted in [Figure 4.10-1](#) sets an upper limit on the number of colors that can be used to code information on an electronic visual display. Other considerations can reduce that limit, though.

If color is allowed to vary along all three of its perceptual dimensions (i.e., brightness, hue, and saturation) for color-coding purposes, as required in [Section 4.2.2](#), the **maximum** number of colors that may be used in a color-coding set *shall* be 24 (Derefeldt & Swartling, 1995). This

limit does not mean that using 24 colors is *recommended*. As [Section 4.3](#) implies, it is best to use the fewest number possible.

The presence of operators with color-vision deficiencies in the ATC population may dictate using fewer than 24 colors. [Section 5.11](#) requires assessing this possibility for prospective color sets.

NOTE:

Discussion: Several standards set much smaller limits for color-coding sets; that is, 5 to 8 colors (ANSI-HFES-100, 2007; ISO 9241-125, 2017; FAA JO 7210.3Z; MIL-HDBK-759C, 1995; MIL-STD-1472G, 2012; SAE ARP4032B, 2013) without clearly stated, valid justification. These limits are reminiscent of (and possibly based on) Miller’s (1956) classic “magical number 7 ± 2 ” paper, which addressed the human span of absolute judgment and immediate memory. Ironically, though, Miller (1956) included discussion of Halsey and Chapanis (1954), which estimated that 11 to 15 colors (differing only in hue and saturation) can be recognized reliably. Further, Hanes and Rhoades (1959), who used colors that differed along all three color-perception dimensions, had one well-practiced subject who learned to recognize 50 colors reliably.

Two standards (ANSI-HFES-200, 2008 and ISO 9241-303, 2011) recommend use of the “focal” color names that were identified by Berlin and Kay (1969) and Crawford (1982) and studied later by Boynton and his colleagues (e.g., Boynton & Olson, 1987; Smallman & Boynton, 1993). A focal color name is one of the 11 basic color names that are used reliably to describe color by people having normal color vision, across most cultures and languages: *red, pink, orange, yellow, brown, green, blue, purple, black, white, and gray* (in English).

Derefeldt and Swartling (1995) tested 35 carefully chosen colors that included five “safety” colors (i.e., a red, yellow, green, blue, and purple having high saturation and intended for alert purposes) and varied along all three color-perception dimensions. The safety colors were shown as 0.86 x 2.7-degree solid (i.e., filled) rectangles, presented simultaneously with the other colors, which were shown as 2.7 x 2.9-degree solid rectangles. The background color was achromatic and set at 58% of the display’s peak white luminance. The ambient illumination was fluorescent and set at a “normal office lighting” level. Six of the seven (color-normal) participants named the same [24 colors from the set](#) reliably and without training, given that they were allowed to use their own, sometimes idiosyncratic names (e.g., “Santa Claus red”) for them.

The 35-color set included three grays but not white or black. Given that the background for most electronic ATC displays is black, most ATC color-coding sets will include a white, and it is likely Derefeldt and Swartling’s participants would have named white reliably, the 24-color limit imposed above may be a bit conservative. Bishop and Crook (1961) estimated that 30 colors can be recognized reliably with little or no training if they are selected carefully and their luminances exceed the background’s.

5.10 Don’t use “spectrally extreme” blues on dark backgrounds

Blue text, symbols, and icons rendered using sRGB = (0, 0, n), where n is greater than zero, often appear blurry when they are shown on dark or black backgrounds, as is probably evident to the reader in [Figure 4.6-1](#). Similar colors can exhibit the same problem if they consist largely of the display’s blue primary. Further, the aforementioned colors and backgrounds can produce

chromostereopsis when red stimuli are present simultaneously, as Figure 4.6-1 shows also. For these reasons, colors having a CIE 1976 v' chromaticity coordinate less than 0.2 **shall not** be used to present text, symbols, or icons on black backgrounds (ANSI-HFES-100, 2007); ISO 9241-303, 2011). Colors that appear acceptably blue but have v' greater than or equal to 0.2 can be created by adding sufficient output from the display's green and/or red primaries.

5.11 Accommodate operators with color-vision deficiencies

The likelihood of color discrimination and recognition problems for color-deficient operators **shall** be assessed using the graphical technique described in [Appendix A](#). In brief, the technique involves drawing a line for each sRGB value in the prospective color-coding set on the CIE 1976 UCS diagram and then adjusting the sRGB values, if needed, to increase distances among lines.

5.12 Color selection for color-coding sets – general guidance

For nominal and ordinal color codes, once the number of colors needed has been determined, their sRGB values must be chosen. Ordinarily, the stereotypical ATC colors listed in [Section 5.2](#) will be included, but (for example) exactly which sRGB triplet from the many possibilities will be used to represent “red”? Similarly, for interval and ratio coding, the designer may have particular color names in mind for the two endpoints, but how will their sRGB values and the intervening ones be chosen? [Appendix C](#) provides general guidance regarding these issues.

5.13 FAA standard palette for color coding critical information

The FAA has developed a standard palette that consists of a color set for coding foreground objects that convey alerts and other critical information, plus a second set for coding weather severity (Gildea., Milburn, & Post, 2018; Gildea et al., in press). The FAA standard palette is suitable for environments where the ambient illumination striking display screens is less than or equal to 40 lux.⁵ It has been shown to be discriminable, recognizable, conspicuous (i.e., easy to spot during visual searches), and legible for observers having normal and deficient color vision, given that redundant coding is used, as required in [Section 4.2](#) for critical information. The standard palette meets all color requirements in this standard, also. Colors from the standard palette may be used to color code non-critical information if they are not needed to code critical information.

5.13.1 Foreground objects

Colors used to code alerts and other critical information that appears in the foreground on displays that are viewed under ambient illumination that is less than 40 lux **shall** be selected from the set shown in Table 5.13.1-I. Their default RGB values **shall** be the sRGB values shown in Table 5.13.1-I. (The color names shown are suggestions and not mandatory.)

5.13.2 Weather severity

Colors used to code weather severity on displays that are viewed under ambient illumination that is less than 40 lux **shall** be selected from the set shown in Table 5.13.2-I. Their default RGB values **shall** be the sRGB values shown in Table 5.13.2-I. (The color names shown are suggestions and not mandatory.)

⁵ The FAA standard palette is derived from experiments in which the ambient illuminance was 40 lux because of the [measurement results reported by E. A. Sierra](#) and Krois et al. (1991).

If all seven (i.e., 0 to 6) FAA-recognized severity levels must be depicted, pattern coding *shall* be used to distinguish severity 1 from 2, 3 from 4, and 5 from 6. Testing *shall* be performed to ensure the pattern allows observers to recognize the weather colors reliably and does not make foreground objects illegible or make their colors unrecognizable.

TABLE 5.13.1-I. FAA standard palette: Foreground colors. (See [Appendix A](#) for graphical representations.)




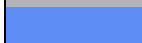








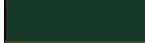


	Color name	u'	v'	%Y	sR	sG	sB	Hex
	White	0.1978	0.4683	100	255	255	255	FFFFFF
	Pink	0.266	0.418	41	246	132	216	F684D8
	Gray	0.1978	0.4683	45	179	179	179	B3B3B3
	Blue	0.17	0.348	28	94	141	246	5E8DF6
	Orange	0.294	0.541	42	254	147	13	FE930D
	Red	0.44	0.518	21.8	255	19	32	FF1320
	Green	0.13	0.54	55	35	225	98	23E162
	Yellow	0.193	0.55	80	223	243	52	DFF334
	Magenta	0.276	0.304	23	216	34	255	D822FF
	Aqua	0.142	0.428	50	7	205	237	07CDED
	Brown	0.241	0.519	34	197	149	91	C5955B

TABLE 5.13.2-I. FAA standard palette: Weather colors.

	Color name	Severity	u'	v'	%Y	sR	sG	sB	Hex
	Black	0	---	---	0.0	0	0	0	000000
	Wx-Green	1 & 2	0.15	0.5	3.2	23	57	40	173928
	Wx-Yellow	3 & 4	0.23	0.54	7.1	90	74	20	5A4A14
	Wx-Red	5 & 6	0.26	0.4	5.0	93	46	89	5D2E59

5.13.3 Palette changes for ambient illumination greater than 200 lux

For displays that are viewed under ambient illumination that exceeds 200 lux, the FAA standard palette may be used but is not mandatory. The Gray and Black shown in Tables 5.13.1-I and 5.13.2-I should be exchanged to provide the gray background required in [Section 5.4.2](#). The luminance of gray and other colors will require adjustment to achieve contrast ratios $\geq 3:1$, as required in [Section 5.5](#).

5.14 Requirements for colors that aren't part of the FAA standard palette

Colors may be used in addition to the FAA standard palette only if: (1) They are used solely to code non-critical information; and (2) It has been demonstrated by experimentation that they are

not confused with any colors in the standard palette that are in use, or vice versa, and do not degrade controller performance in any other way. Colors that do not meet the aforementioned criteria *shall not* be used.

5.15 Allowing operators to customize colors

5.15.1 Disallow changing the chromaticity of alerts and other critical information

ATC software *shall not* allow operators to change the CIE chromaticity coordinates of colors used to convey alerts or other critical information. The software *shall* protect those coordinates against attempts to circumvent the lack of an intentionally provided means to change them.

5.15.2 Allowable method for changing the chromaticity of non-critical information

ATC software should allow operators to change the chromaticity of colors that are not used to convey alerts or other critical information. If this capability is provided, it *shall* function solely by allowing the operator to designate a displayed object and select alternative chromaticities for it from a finite palette. The alternatives *shall* have the same luminance as the object's default color and have hues that are similar to the default color. All alternatives *shall* be tested beforehand and have been shown not to degrade operator task-performance. (See [Appendix C](#) for recommended mockup-test procedures.) No other chromaticity-change methods (e.g., sliders or color wheels) are permissible.

5.15.3 Allow adjustment of display's peak white luminance

ATC systems *shall* allow operators to change the peak white luminance of their displays so that the luminances of displayed objects change in proportion to that luminance without altering their chromaticities or luminance-contrast ratios. This function may be implemented for liquid-crystal displays (LCDs) by allowing operators to adjust the backlight's luminance.

5.15.4 Allow adjustment of object luminances

ATC software *shall* allow operators to designate a displayed object and adjust its luminance, so it may be emphasized or de-emphasized to suit the operator's needs at that moment.

5.15.5 Allowable method for changing object luminances

To avoid unintended changes in chromaticity, ATC software *shall* make the luminance changes described in Section 5.14.4 *solely* by allowing the operator to command a new desired luminance and then using the equations in IEC 61966-2-1:1999 to compute new sRGB values that have the same CIE chromaticity coordinates as before. ATC software *shall not* make luminance changes by scaling sRGB values (e.g., halving the values to reduce an object's luminance) because that approach will alter the object's chromaticity coordinates in most cases.

5.15.6 Allow single-point and global changes

The color-customizing functions described above *shall* allow the operator to choose easily between changing: (1) the operator-designated displayed object only; (2) all displayed objects of the same type as the operator-designated one simultaneously; or (3) all displayed objects that form a natural group, such as datablocks and aircraft symbols.

5.15.7 Allow operators to save customized color sets

ATC software *shall* allow operators to create presets by saving color sets they create using the customizing functions described above.

5.15.8 Allow operators to restore customized color sets

ATC software *shall* allow operators to restore their presets to any display that is controlled by that software, regardless of whether a preset was created for the display the operator is using currently.

5.15.9 Provide a color-reset function

ATC software *shall* provide a function that allows operators to reset all colors to their default sRGB values quickly and easily.

5.15.10 Perform an automatic color-reset on restart

ATC software *shall* reset all colors to their default sRGB values and send a command to the display that selects its sRGB-preset state, as described in [Section 5.16.2](#), each time the software is restarted.

5.15.11 Provide an sRGB preset for operators

ATC software *shall* provide a function that allows operators to invoke the sRGB reset described in [Section 5.16.2](#).

5.16 Display hardware color requirements

Vendors should test displays procured for the uses covered by this standard individually before delivery to ensure they meet the requirements in this section. The displays should also be warranted by the vendor to meet the requirements.

5.16.1 Conform to sRGB

Displays procured for the uses covered by this standard *shall* be capable of conforming to the white-point chromaticity, RGB primaries, and gamma required by the sRGB color space described in IEC 61966-2-1:1999.

5.16.1.1 sRGB white-point chromaticity accuracy

The result obtained by calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the White-Point Accuracy test described in IDMS 1.0.3 *shall* yield $\Delta u'v'$ no greater than 0.012 relative to a CIE standard illuminant D₆₅ reference white (TCO, 2015).

5.16.1.2 sRGB-primary chromaticity accuracy

The result obtained by calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the Full-Screen Primary Colors (R, G, and B) test described in IDMS 1.0.3 *shall* yield $\Delta u'v'$ no greater than 0.012 relative to each of the three IEC 61966-2-1:1999 sRGB primaries (TCO, 2015).

5.16.2 Provide a software-triggered sRGB preset

Displays procured for the uses covered by this standard *shall* be capable of responding correctly to a command received over its workstation interface to put the display in an sRGB-preset state that satisfies the requirements in Section 5.16.1. The display should always default to its sRGB-preset state when it is turned on.

5.16.3 Maximum black luminance

The result obtained by calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the Image-Signal Black test described in IDMS 1.0.3 with the display's brightness control at its maximum setting *shall* yield a luminance no greater than 2 cd/m² (TCO, 2015).

5.16.4 Minimum peak-white luminance

The result obtained by calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the Peak White test described in IDMS 1.0.3 with the display's brightness control at its maximum setting *shall* yield a luminance no less than 200 cd/m² (TCO, 2015).

5.16.5 Luminance non-uniformity at operator eye-position

The result obtained by calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the Sampled Vantage Point Uniformity test described in IDMS 1.0.3, using the 9-point option, full-screen white test pattern, and measuring at the expected operator eye-position and viewing distance, *shall* yield a luminance non-uniformity value less than 41% (ANSI-HFES-100, 2007; ISO 9241-303, 2011).

5.16.6 Chromaticity non-uniformity at operator eye-position

The result obtained by calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the Sampled Vantage Point Uniformity test described in IDMS 1.0.3, using the 9-point option, full-screen white test pattern, and measuring at the expected operator eye-position and viewing distance, *shall* yield $\Delta u'v'$ no greater than 0.025 (TCO, 2015).

5.16.7 Luminance non-uniformity off-axis

The result obtained by calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the Viewing-Angle Luminance Change Ratio test described in IDMS 1.0.3, measuring at ± 60 degrees horizontally with respect to the normal, *shall* yield a luminance change ratio no greater than 0.41 (ANSI-HFES-100, 2007; ISO 9241-303, 2011).

5.16.8 Chromaticity non-uniformity off-axis

The result obtained by calibrating the display using the process described in [Appendix B](#) and then measuring it in accordance with the Viewing-Angle Color Variation test described in IDMS 1.0.3, measuring at ± 60 degrees horizontally with respect to the normal and full-screen test patterns. The measured colors shall include the FAA standard palette foreground colors (Table 5.13.1 I) and weather colors (Table 5.13.2 I) and white, the red, green, and blue primaries, the

cyan, magenta, and yellow secondaries (all seven at their maximum luminances). All of the measured colors except Black *shall* yield $\Delta u'v'$ no greater than 0.025 (TCO, 2015).

5.16.9 Pixel fill factor for LCDs

Measuring an LCD in accordance with the Pixel Fill Factor test described in IDMS 1.0.3 *shall* yield a fill factor no less than 90% (ANSI-HFES-100, 2007).

5.16.10 Minimum LCD pixel density

LCDs *shall* have a pixel density no less than 30 pixels/degree at the expected operator viewing distance and *shall* always be operated in their native-resolution mode (ANSI-HFES-100, 2007; NASA-STD-3001, 2011; NASA HIDH, 2014; TCO, 2015).

5.16.11 Impermissible pixel faults

5.16.11.1 Stuck lines or rows of pixels

The display *shall not* have entire lines or rows of pixels that are: (1) stuck on; (2) stuck off; or (3) stuck at an intermediate level.

5.16.11.2 Visible temporal variability of lines or rows of pixels

The display *shall not* have entire lines or rows of pixels that exhibit temporal variability that is apparent to the operator in the work environment when the input video signal is constant.

5.16.11.3 Visibly stuck or temporally variable pixels, pixel subareas, and subpixels

The display *shall not*, to extents that are apparent to the operator in the work environment, have individual pixels, pixel subareas, or subpixels that are: (1) stuck on; (2) stuck off; (3) stuck at an intermediate level; or (4) exhibit temporal variability when the input video signal is constant (ISO 9241-303, 2011; MIL-HDBK-87213A, 2005; SAE AS8034B, 2011).

5.16.12 Required temporal characteristics

The display *shall not* exhibit flicker, directionally variant judder, moving-line contrast degradation or spreading, gray-scale aberrations, dynamic false contour degradation, inversion edge artifacts, or low dynamic contrast for moving patterns, as defined in the Flicker Visibility and Motion Artifacts sections of IDMS 1.0.3, that are apparent to the operator in the work environment.

5.16.13 Provide display-calibrator compatibility

A variety of COTS colorimetric instruments with associated proprietary software (known generally as *display calibrators*) are available that are designed specifically to calibrate color displays, in conjunction with a COTS computer. Displays procured for the uses covered by this standard *shall* be capable of interfacing correctly with at least one COTS display calibrator and COTS computer that can adjust the display to satisfy the requirements in [Section 5.16.1](#) and accomplish the display color calibration process described in [Appendix B](#). The vendor *shall* identify one or more COTS display calibrators and COTS computers that meet these requirements.

6 NOTES

6.1 Intended application

This standard provides color-usage guidelines that may be used as design requirements for all future ATC acquisitions and all upgrades of current systems involving ATC displays in tower, terminal, en route, oceanic, and other air traffic operations facilities. It may be extended to auxiliary displays, such as those depicting weather systems and traffic management systems.⁶

6.2 Tailoring

Tailoring is the process of selecting and evaluating individual requirements to determine the extent to which they apply to a specific system or piece of equipment. It includes the process of modifying these requirements to ensure that there is an optimal balance between operational needs and cost. To ensure proper application of this standard, the requirements in Sections 4 and 5 of this standard should be tailored to exclude any unnecessary requirements when generating invitations for bids, requests for proposals, and contractual statements of work.

6.2.1 General guidance

Design requirements such as those contained in this document must be worded generally so they may be applied to many different system applications. Before they can be applied to a specific system or piece of equipment however, these generally worded requirements often need to be converted into system- or application-specific requirements or criteria.

Tailoring may not always be possible. If the specifics of a system are not known in advance, a section or subsection of this standard may need to be cited in its entirety, with tailoring occurring later in the process.

6.2.2 Tailoring to reduce cost

Some requirements contained in this document may not be applicable to a specific system. Indeed, the application of every requirement to a single system might result in a system that is cost prohibitive. Tailoring the requirements to ensure applicability to a specific system avoids unnecessary effort and overly restrictive design, thereby reducing cost.

6.2.3 Joint responsibility

Tailoring is the joint responsibility of a coalition of human factors experts, vendors or system developers, operators, and program managers. The members of this coalition must have a thorough understanding of task requirements and operator or maintainer characteristics. Each member has something unique to contribute to the process. Operators and maintainers have knowledge of the nuances of task handling, people from the program office and vendors have knowledge of the costs involved in implementing system requirements, and human factors experts have knowledge of human factors considerations in all aspects of the system life cycle. Together, these members can determine which of the items will provide the most benefit overall.

⁶ The requirements and criteria contained in this standard do not apply to the design approval of aircraft, which is covered currently in 14 CFR 21, 23, 25, 27, and 29.

6.2.4 Process

As a first step, a human factors expert must review this document and identify those requirements that are potentially relevant to the acquisition being considered. For a complex system or one with many components, the resulting list may be extensive. Once all potentially relevant requirements have been identified, they should be reviewed to decide which are most appropriate for the particular acquisition, and whether they can be used as-is or require tailoring.

6.3 Implementers' points of reference

For additional guidance regarding implementation of the color palette on current and future system displays, contact the Human Factors Technical Representative for your program.

APPENDIX A. COLOR CALCULATIONS

A.1 Size-correction coefficients for Eqn. 1

Carter (1989) provided the following equations for calculating the CIELUV size-correction coefficients. L. D. Silverstein (personal communication, 1988) derived them, using data reported by Judd and Yonemura (1969):

$$K_L^* = 1.0366 - e^{0.15263 - 0.05766A} \quad \text{for } 0 < A < 60 , \quad (3)$$

$$K_u^* = 0.008991A - 0.0065 \quad \text{for } 0 < A \leq 32 , \quad (4)$$

$$= 0.0257A - 0.5403 \quad \text{for } 32 < A < 60 , \quad (5)$$

$$K_v^* = 0.005446A - 0.042 \quad \text{for } 0 < A \leq 32 , \text{ and} \quad (6)$$

$$= 0.031A - 0.8594 \quad \text{for } 32 < A < 60 , \quad (7)$$

where A is the visual angle subtended by the stimulus in arcmin. For $A \geq 60$ arcmin, $K_L^* = K_u^* = K_v^* = 1$.

A.2 Plotting and evaluating confusion lines

A common graphical technique for gauging whether colors are apt to be hard for color-deficient observers to discriminate involves drawing their *confusion lines* on a chromaticity diagram. Confusion lines have different points of origin for each of the three main classes of color-vision deficiency (protan, deutan, and tritan) and intersect the chromaticity coordinates for each color of interest. A confusion line is so-called because any chromaticity coordinates that lie on it will be difficult or impossible for observers having the associated type of color-vision deficiency to discriminate.

A.2.1 Drawing the CIE 1976 UCS diagram

The CIE 1976 UCS diagram is suited best for the purposes herein because it provides an approximately uniform representation of human color-difference perception. An easy way to obtain the data needed to draw it is to visit <http://www.cvrl.org/cmfs.htm>, scroll down to the section labeled "CIE 1931 2-deg, XYZ CMFs", and click the second of the two download options. That download is a comma-separated values (.csv) file, containing the CIE 1931 XYZ color-matching functions, as defined in CIE 15:2004, from 360 to 830 nanometers (nm) in 1-nm increments. (The first option uses 5-nm increments.) It can be opened directly by programs such as Microsoft Excel. (The examples shown in this appendix were created using Excel.)

The next step is to create two new columns that convert each XYZ triplet to its corresponding x and y chromaticity coordinates, using the equations:

APPENDIX A

$$x = \frac{X}{X + Y + Z} \quad \text{and} \quad (8)$$

$$y = \frac{Y}{X + Y + Z} \quad . \quad (9)$$

Next, create two more columns by converting to the corresponding u' and v' chromaticity coordinates, using the equations:

$$u' = \frac{4x}{-2x + 12y + 3} \quad \text{and} \quad (10)$$

$$v' = \frac{9y}{-2x + 12y + 3} \quad . \quad (11)$$

The final step is to graph the u' and v' coordinates from 360 to 830 nm, using a function that connects the points, draw a straight line connecting the coordinates at 360 and 830 nm, and draw appropriate axes that are scaled equally. The result should resemble Figure A.2.1-1.

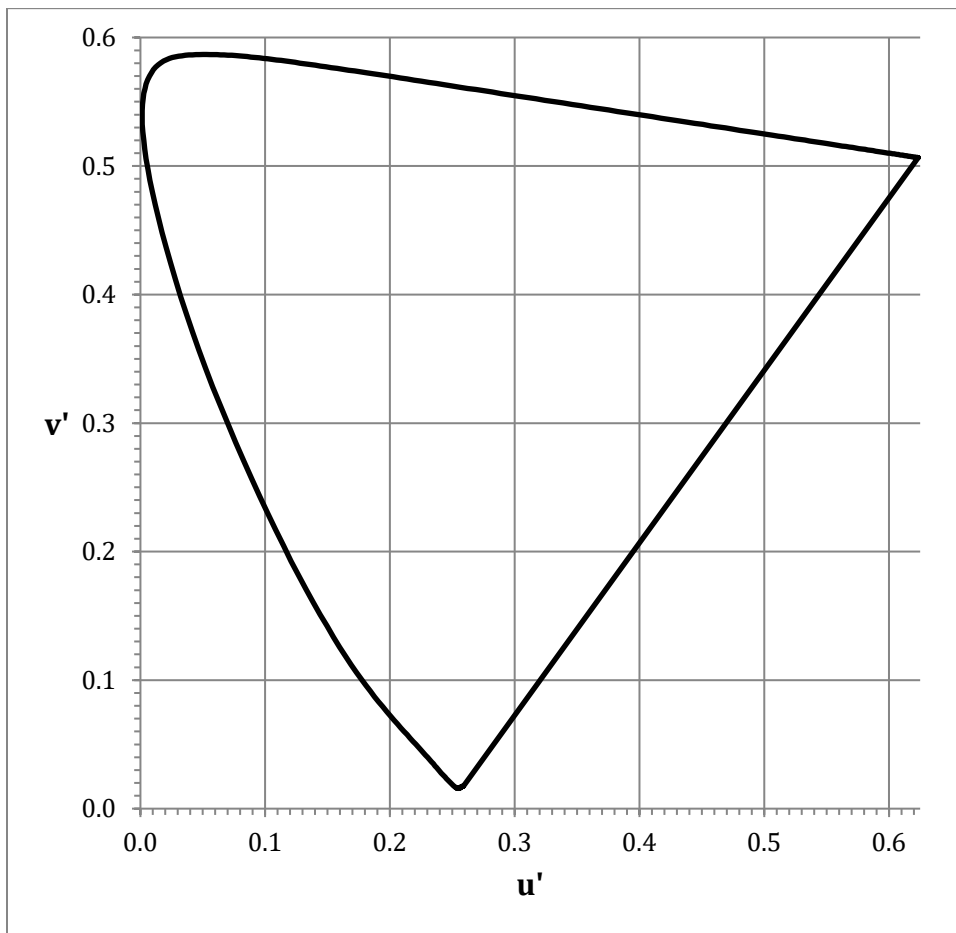


FIGURE A.2.1-1. CIE 1976 UCS diagram.

A.2.2 Converting sRGB values to u' and v'

If the color set under consideration is expressed in terms of sRGB values, they can be converted to their corresponding u' and v' chromaticity coordinates using the equations in IEC 61966-2-1:1999 to convert the sRGB values to their corresponding CIE 1931 XYZ tristimulus values, as defined in CIE 15:2004, and then using Equations 8 through 11 (above) to get u' and v' .

A.2.3 Plot the colors' u' and v' coordinates

The first step in drawing the confusion lines for the color set is to plot each color's u' and v' coordinates on the CIE 1976 UCS diagram, as illustrated in Figure A.2.3-1. Adding the triangle defined by the sRGB primaries (shown in Table A.2.3-I) to the figure is helpful because it shows the range of chromaticity coordinates an sRGB-compliant display can produce (i.e., its chromaticity gamut) and how the colors are spaced within that range.

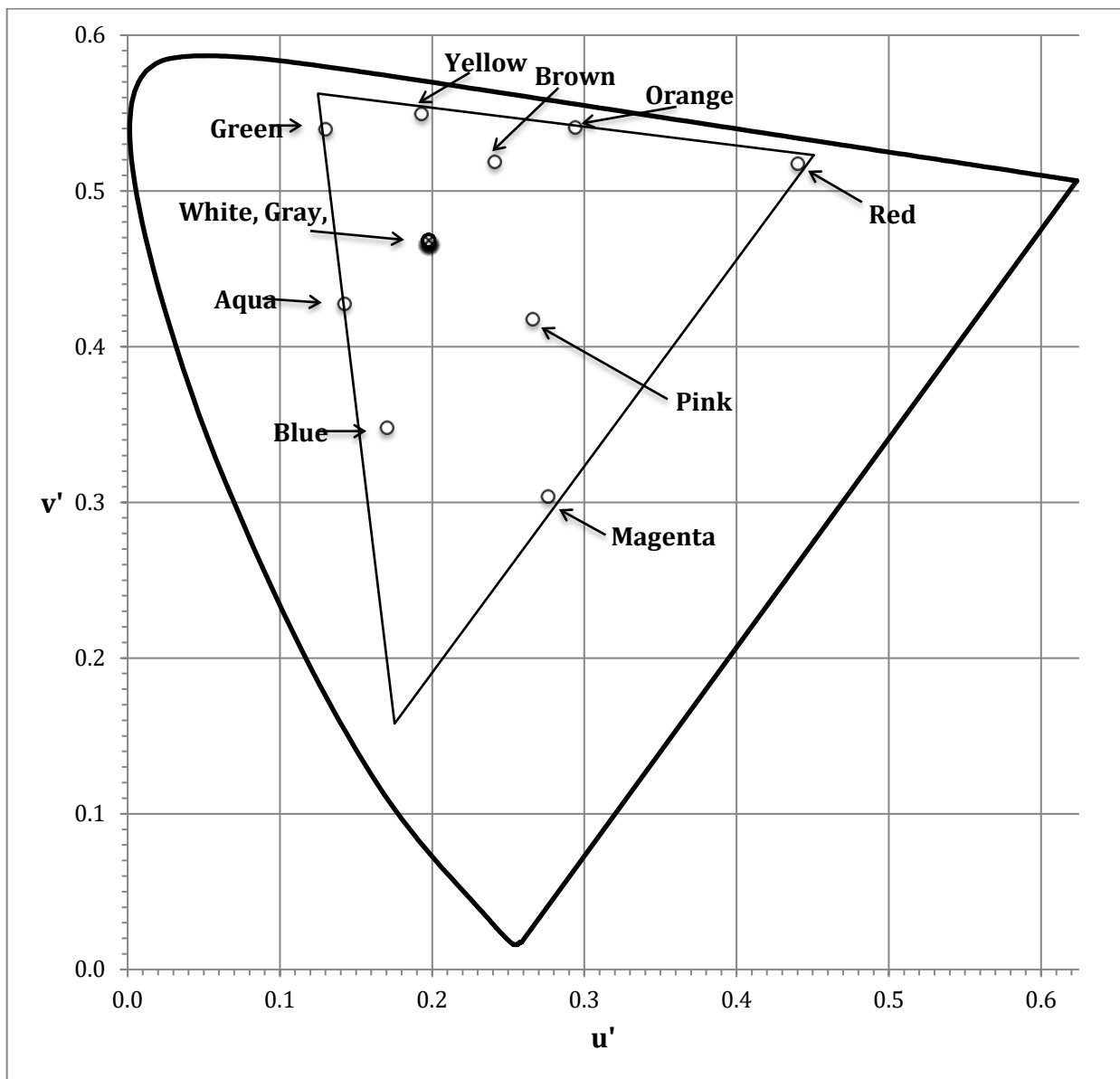


FIGURE A.2.3-1. The FAA standard palette's foreground colors.

APPENDIX A

TABLE A.2.3-I. sRGB primaries.

sRGB Primary	u'	v'
Red	0.45	0.52
Green	0.13	0.56
Blue	0.18	0.16

A.2.4 Drawing confusion lines

The next step is to draw a line through each color's location, starting from the origin associated with each main class of color deficiency. These three origins are called the *copunctal points*; a recommended set is shown in Table A.2.4-II and the results are shown in Figure A.2.4-1.

TABLE A.2.4-II. Recommended copunctal points.¹

Deficiency class	u'	v'
Protan	0.6579	0.5013
Deutan	-36.0000	6.0000
Tritan	0.2573	0

¹ These copunctal points are taken from Wyszecki and Stiles (1982), Table 1(15.4.2), p. 464. As footnote *b* to that table mentions, others have been derived. The numerical differences among them are small, though, and the practical consequences of using others for the purposes herein are probably negligible.

APPENDIX A

Examination of Figure A.2.4-1 reveals three noteworthy points: (1) Several colors in the set lie on or near the gamut's edges, meaning they are at or near the display's saturation limits (which means also that those colors have at least one sRGB value that is either zero or nearly so); (2) Although none of the colors lie exactly on the same line, several are close to doing so, which means protans may have difficulty discriminating them unless they differ obviously in luminance; and (3) Discrimination problems become more likely as a color nears the protan copunctal point.

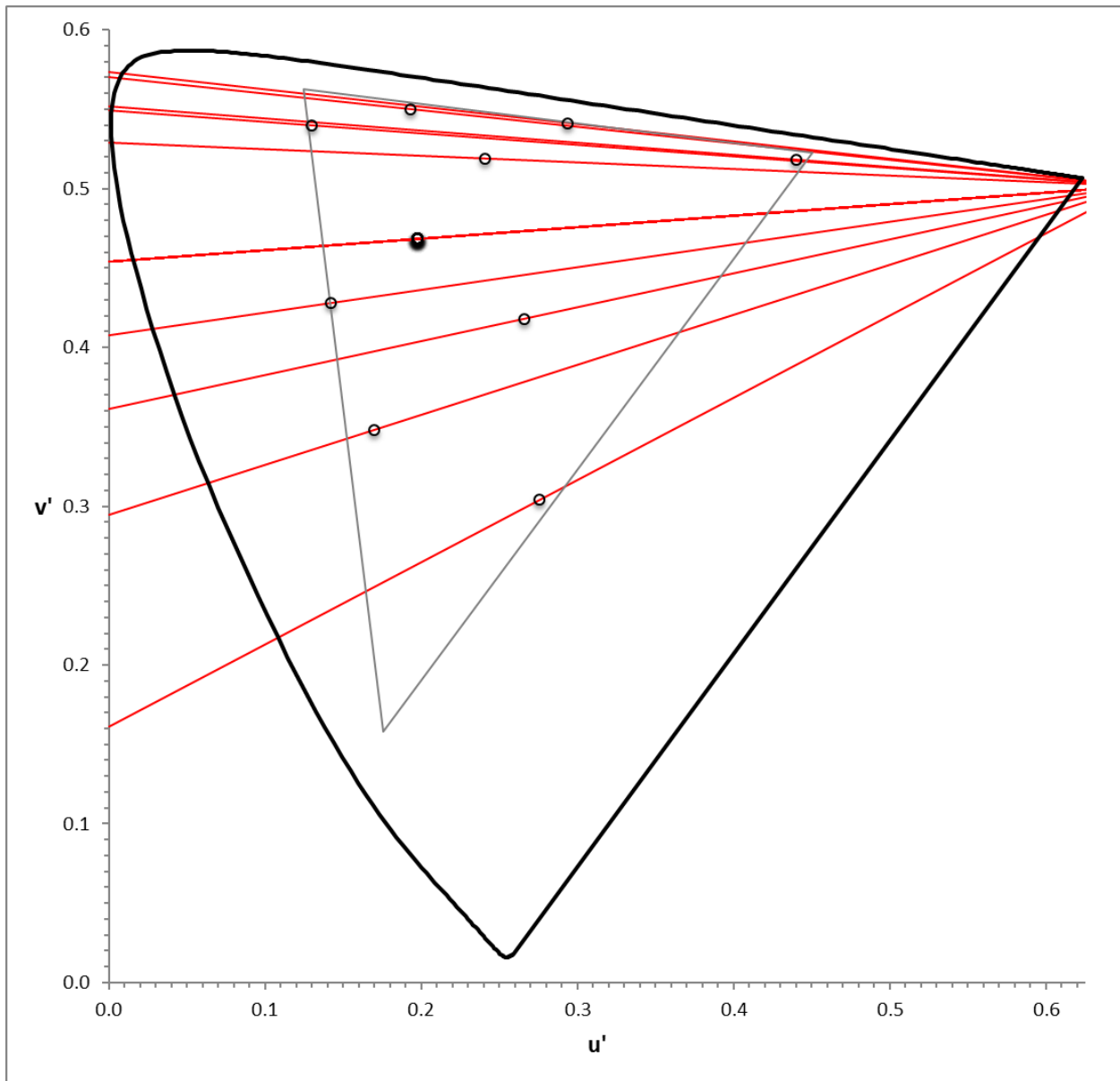


FIGURE A.2.4-1. Protan confusion lines for the FAA standard palette's foreground colors.

APPENDIX A

Figure A.2.4-2 shows the color set's deutan and tritan confusion lines. It can be seen that plotting both on one figure does not complicate interpreting the figure especially because tritan lines are roughly vertical, whereas deutan lines are roughly horizontal. It can be seen also that several colors are apt to be difficult for deutan and tritans to discriminate, some of which are the same ones that may pose problems for protans. Discrimination problems for tritans become more likely as a color approaches the tritan copunctal point. The analogous problem for deutans is miniscule, though, because the deutan copunctal point lies far away from the CIE 1976 UCS diagram's boundary, making deutan confusion lines on that diagram nearly parallel.

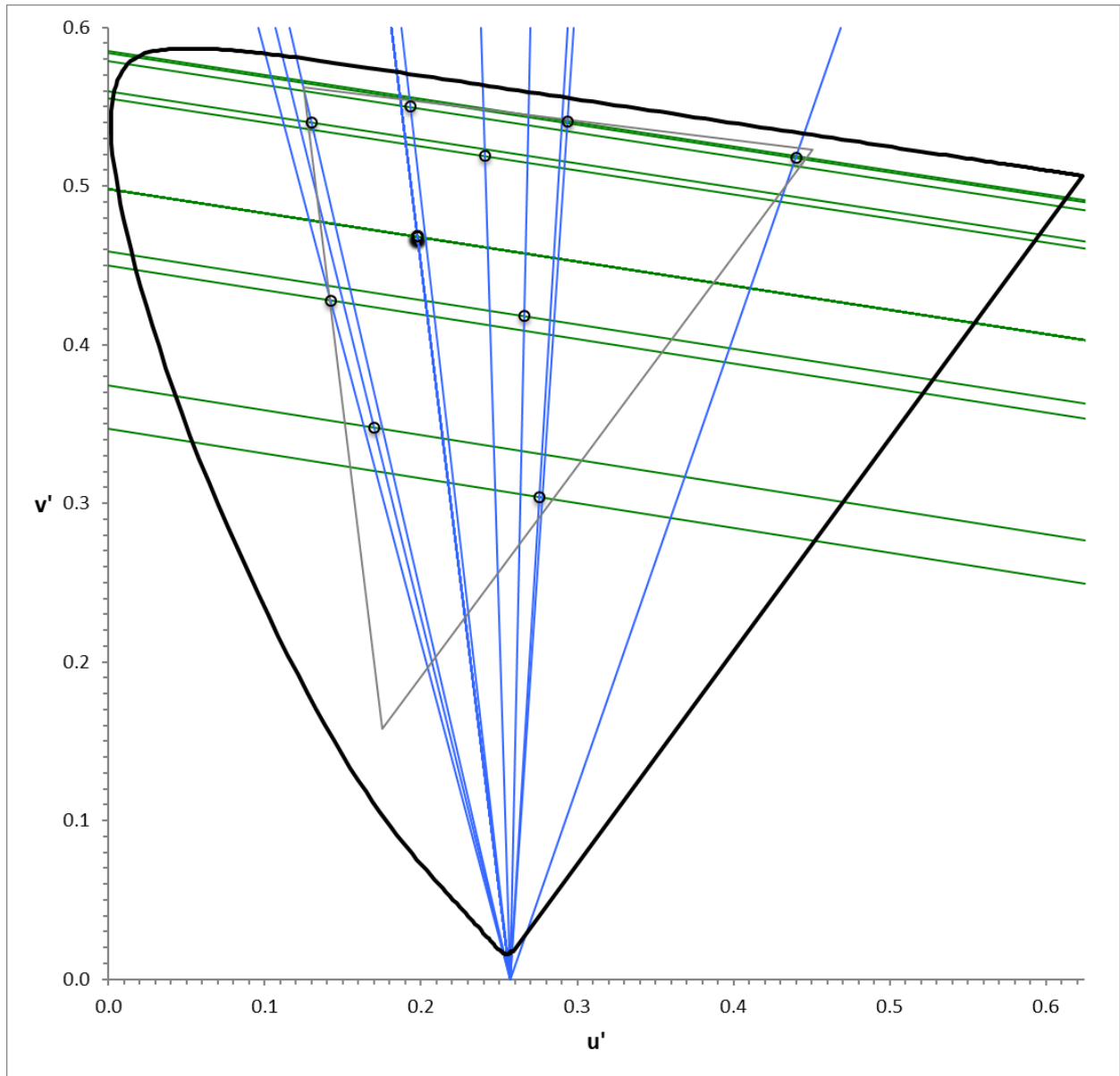


FIGURE A.2.4-2. Deutan and tritan confusion lines for the FAA standard palette's foreground colors.

APPENDIX A

Figure A.2.4-3 shows all three classes of confusion lines on one figure. Its purpose is to illustrate why doing so can be a bad idea: Protan and deutan confusion lines are both roughly horizontal, so drawing both on the same figure can create overlapping lines that impede interpretation.

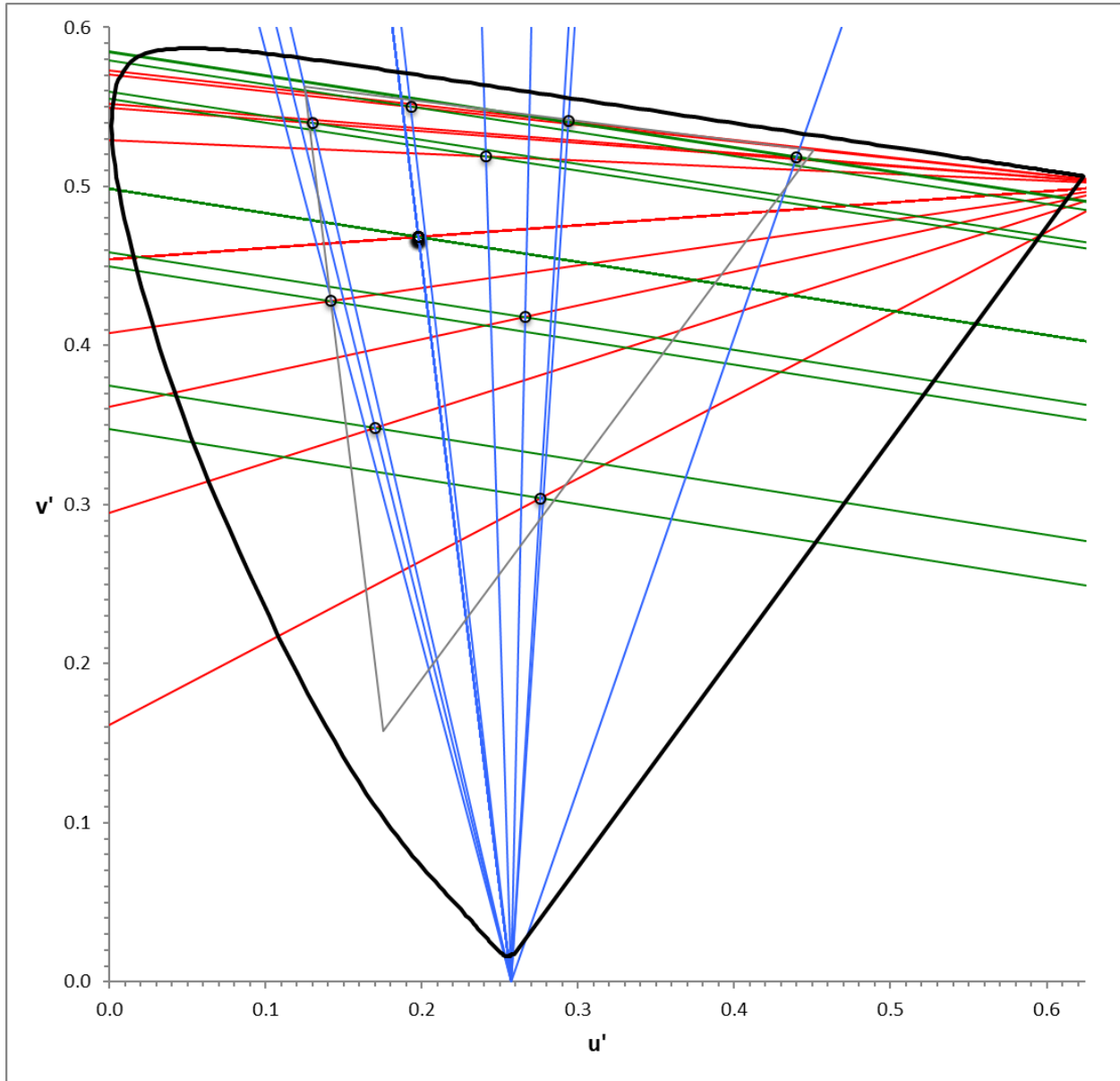


FIGURE A.2.4-3. Protan, deutan, and tritan confusion lines for the FAA standard palette's foreground colors.

A.2.5 Interpreting confusion lines

The preceding figures make it evident that the colors should be adjusted to increase their separation and/or include obvious luminance differences to improve their discriminability for people having color-vision deficiencies. (The FAA standard palette uses the latter tactic.) It is natural to wonder what minimum separation is required to ensure discriminability. Regrettably,

APPENDIX A

the scientific literature does not provide a definitive minimum-distance requirement of that type for the CIE 1976 UCS diagram (or any other chromaticity diagram) for color-normals, let alone people with color-vision deficiencies.

There is, however, a “rule of thumb” that seems to have originated and been used in color-television broadcasting literature (e.g., Jones, 1968; Sproson, 1971, 1978, 1983). This criterion is a distance of 0.00384 on the CIE 1976 UCS diagram, which is rounded up to 0.004 in some publications. That distance, however, is treated as the minimum that can be discriminated by color-normal viewers. IDMS (2012) states in its Appendix B.1 that the colors must be touching for that criterion to be valid. (The ability to discriminate color differences decreases as the colors’ spatial (and temporal) separation increases, meaning the minimum-discriminable distance on the chromaticity diagram increases.)

The preceding information implies that confusion-line separations less than 0.00384 may cause discrimination problems for color-deficient viewers, and differences in chromaticity coordinates less than 0.00384 may cause the same problem for color-normals. It is prudent, therefore, to adjust a color-coding set so the confusion-lines’ and colors’ separations on the chromaticity diagram exceed that value, at the least. Better still is to adjust the colors so those separations are maximized without compromising their desired color appearances (e.g., “red,” “green,” etc.) for color normals. This goal can be approached by viewing the colors (assuming the viewer is color-normal) on a display that has been calibrated, using the process described in [Appendix B](#), and adjusting their sRGB values while watching also how the confusion lines move in response.

Ultimately, though, a prospective color-coding set that has been developed using the technique described above should be validated by using the mockup testing recommended in [Appendix C](#) before finalizing its sRGB values. Mockup testing that includes color-deficient viewers allows the differences in protans’ perceptions of luminance and luminance contrast (mentioned in [Section 4.2.2](#)) to be considered. Confusion-line analysis does not take luminance differences among the colors into consideration, so mockup testing may show that a color-coding set is more discriminable than its confusion lines alone imply.

APPENDIX B. DISPLAY COLOR CALIBRATION

B.1 Purpose

Personnel at facilities may find that newly delivered displays do not always produce the intended colors accurately enough; further, displays' color-reproduction characteristics tend to change over time. This appendix recommends procedures to overcome these problems.

B.2 Calibration schedule

A technician should calibrate displays used for the purposes covered by this standard before they are placed into service and annually, or sooner if an operator requests it. It may be desirable to establish a more frequent schedule if experience with a display shows it is needed.

B.3 Calibration tags

Technicians should place calibration tags similar to those shown in Figure B.3-1 on the back of all displays used for the purposes covered by this standard to help ensure that the calibration schedule for each display is met.



FIGURE B.3-1. Example of a calibration tag.

B.4 Calibration process

COTS display calibrator software typically steps the user through a series of menu options and performs a sequence of automated measurements and adjustments of the display and computer graphics card that calibrate the display. (They produce a color profile for the display also, typically, but these profiles are not needed for the purposes herein.) The software may also be capable of displaying measurement results afterward that indicate whether the display meets requirements contained in [Section 5.16](#).

Technicians should perform display color calibration using a vendor-approved calibrator and computer to run the calibrator software. Calibration should be performed with the display in its sRGB-preset state, as described in [Section 5.16.2](#). Technicians should consult the calibrator's manual to identify and select menu options that conform to the sRGB standard described in IEC 61966-2-1:1999.

B.5 Calibrator calibration

Technicians should be aware that display calibrators require periodic calibration or replacement and should consult the calibrator's manual or vendor to determine an appropriate schedule.

B.6 Operator adjustment of display controls

Operators should be discouraged from adjusting display controls that alter hue or saturation because these actions may degrade the discriminability, recognizability, and/or legibility of the colors and necessitate recalibration. Adjustments of overall brightness and contrast are permissible, though, because operators can correct them easily if they cause viewing problems.

APPENDIX C. Designing ordinal, interval, and ratio color codes

C.1 Choosing specific sRGB values to represent color names

[Derefeldt and Swartling \(1995\)](#) provided English names and the L^* , u' , and v' values for their colors. Those numbers can be converted to normalized luminances and corresponding sRGB values, using the information provided in CIE 15:2004 and IEC 61966-2-1:1999, yielding the results shown in Table C.1-I. (Their display's color gamut was slightly larger than the sRGB gamut; this is why two of the sG values are > 255 .) Examination of the colors produced by those sRGB values on a display that has been calibrated using the process described in [Appendix B](#) may reveal good choices or starting points.

TABLE C.1-I. The 24 reliably named colors from Derefeldt and Swartling (1995).

Color Name	%Y	u'	v'	sR	sG	sB
Dark yellow	51.37	0.214	0.550	207	193	23
Orange	24.72	0.301	0.528	206	111	51
Plum	6.87	0.251	0.446	102	62	83
Medium purple	24.92	0.184	0.363	118	130	221
Chicken yellow	60.30	0.201	0.527	208	209	113
Ice-cream orange	39.76	0.236	0.511	207	161	112
Dark rose; Wine red	17.84	0.274	0.466	170	95	113
Light blue	57.39	0.161	0.426	122	210	252
Dark green; Green	25.75	0.132	0.541	34	160	66
Beige	49.56	0.187	0.492	172	193	159
Brown	15.19	0.282	0.532	157	94	36
Dark gray	14.19	0.169	0.460	77	111	113
Medium gray	39.34	0.173	0.464	132	177	175
Cerise	37.97	0.233	0.423	207	145	207
Bright blue; Flag blue	23.52	0.159	0.317	38	130	253
Light gray	68.39	0.175	0.467	175	225	220
Tomato red; Santa Claus red	12.12	0.355	0.520	170	62	37
Pigeon blue; Thunder blue	20.32	0.165	0.402	79	128	176
Jade; Grayish green	28.12	0.141	0.457	31	160	160
Signal red	13.36	0.441	0.520	205	14	17
Signal green	79.15	0.128	0.561	49	266	23
Signal blue	8.10	0.174	0.173	5	30	253
Signal yellow	91.46	0.176	0.555	208	265	28
Signal purple	21.23	0.270	0.299	205	37	250

APPENDIX C

Post and his colleagues (Post & Calhoun, 1988, 1989; Post & Greene, 1986) studied the frequency with which color-normal participants used a set of color names (which included the focal color names) to describe 210 color stimuli that spanned the range of chromaticities their display could produce. The colors' luminances were adjusted to match the brightness of CIE standard illuminant D₆₅ at 30 cd/m². The viewing conditions included black and white backgrounds, 0-, 350-, and 2050-lux fluorescent ambient-illumination levels, and stimulus shapes that represented symbology (unfilled squares subtending 20 arcmin visually) and area fills (solid circles subtending 2 degrees visually). For each combination of viewing conditions, they produced figures showing the probability of obtaining the name the participants chose most often for each stimulus on CIE 1976 UCS diagrams. Those figures can be used to estimate the CIE 1976 chromaticity coordinates that are most apt to match operators' expectations for each color name, given similar stimuli and viewing conditions.

Once prospective sRGB values have been chosen, the method described in [Appendix A](#) is needed to check for potential discrimination problems they may cause color-deficient operators and make adjustments, as needed. Ideally, the values should then be tested by showing image mockups that include all anticipated color combinations under realistic viewing conditions to color-normal and color-deficient observers who can pass the ATCOV. Mockup testing should use the same display model that will be used in the field and the display should be calibrated first, using the process described in [Appendix B](#). Testing should assess the colors' discriminability and recognizability, as well as how easily they are spotted during visual search and the legibility of text, symbols, and icons that will be rendered using those colors, against all potential backgrounds.

C.2 Choosing the perceptual dimension and endpoints

Deciding which of the three dimensions of color perception is the most “intuitively clear” to a viewer for a color code, as advised throughout [Section 4.1.2](#), can be difficult. In some cases, obvious population stereotypes exist for specific contexts. For example, hues ranging from green to red will be understood readily to represent increasing danger if the user knows, expects, or infers that an object represents something that can vary importantly in danger. For the same reasons, hues ranging from blue to red are used often to show increasing temperature and hues ranging from pale to dark, saturated blue are used often to show increasing water depth. Obvious stereotypes like these should always be used when they exist, and make choosing the colors to represent the endpoints easy.

In other cases, choosing how to imply “more” of something can be arbitrary. For example, using decreasing brightness to show increasing age of a history trail, as shown in [Figure 4.1.2.4-1](#), may seem to be an obvious choice, but decreasing saturation, ending with white, followed by decreasing brightness could be used instead if showing a longer history is desired. Depicting increasing precipitation with hues ranging from pale to dark, saturated blue, thereby taking advantage of the aforementioned “water” stereotype, might be a good choice. If the designer's intent is to associate increasing precipitation with increasing danger, though, using the green-to-red span might be better. If one or more additional variables, such as wind shear or icing probability were combined with precipitation to compute a danger level, the green-to-red span would definitely be better.

APPENDIX C

When choosing the perceptual dimension and endpoints to use, the following considerations may be helpful:

- Hue provides a wide span of discriminable options and poses no visibility problems if stimulus luminance, luminance contrast, and size are adequate. There are many context-dependent population stereotypes for hue, though, so one must take care not to include hues that can be taken to imply unintended, inappropriate meanings. The choices for the endpoint colors should take advantage of population stereotypes whenever suitable ones exist.
- Saturation poses no visibility problems if stimulus luminance, luminance contrast, and size are adequate, but provides a smaller range of discriminable options than hue – especially as stimuli showing different levels become increasingly distant from one another. The two endpoint colors should be white and the highest saturation the display can produce for the chosen hue, usually, but deciding which one should represent the highest level of the variable being coded is context dependent.
- Brightness provides a wider range of discriminable options than saturation, especially as stimuli showing different levels become closer to one another, but black may not be usable if the background is gray or the objects showing different levels are not adjacent and must all be visible. The two endpoints should be the brightest and most saturated rendition of the chosen hue the display can produce and either black or gray. Again, the choice of which endpoint should represent the highest level is context dependent.

An algorithm developed by Breslow, Trafton, McCurry, and Ratwani (2009) may also be helpful for creating color scales suitable for depicting categorical or ordinal data.

APPENDIX D. ACRONYMS AND ABBREVIATIONS

ADA	Americans with Disabilities Act
arcmin	Minutes of arc
ATC	Air traffic control
ATCOV	Air Traffic Color Vision Test
CAMI	Civil Aerospace Medical Institute
cd	Candela
cd/m ²	Candelas per square meter
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
CIELAB	The CIE 1976 (L*a*b*) color space described in CIE 15:2004
CIELUV	The CIE 1976 (L*u*v*) color space described in CIE 15:2004
COTS	Commercial off-the-shelf
CVD	Color-vision deficient
dBZ	Decibels relative to Z
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
Hz	Hertz
ICC	International Color Consortium
ICDM	International Committee For Display Metrology
IDMS	Information Display Measurement Standard
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
L cone	Long-wavelength-sensitive cone
LCD	Liquid-crystal display
lm	Lumen
lm/m ²	Lumens per square meter
lux	Lumens per square meter
M cone	Medium-wavelength-sensitive cone
NCV	Normal color vision
nm	Nanometer
RGB	Red, green, and blue
S cone	Short-wavelength-sensitive cone
SI	Système International
sr	Steradian
sRGB	Standard RGB
STARS	Standard Terminal Automation Replacement System
TCO	Tjänstemännens Centralorganisation (Swedish Confederation of Professional Employees)
UCS	Uniform chromaticity scale
W	Watt
Z	Equivalent reflectivity of a radar signal reflected off a remote object in mm ⁶ per m ³

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APPENDIX E

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CONCLUDING MATERIAL

Custodian:

FAA ANG-C1 (Human Factors Division)

Preparing activity:

FAA ANG-C1 (Human Factors Division)

Review activities:

AJE (En Route & Oceanic)

AJP (Systems Operations)

AJT (Terminal)

CAMI AAM-500