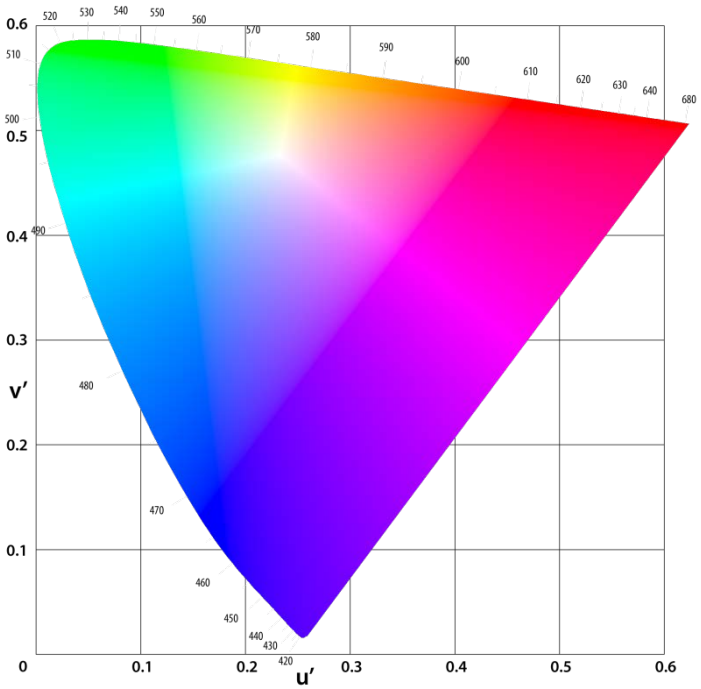
Use of Color on Airport Moving Maps and Cockpit Displays of Traffic Information (CDTIs)

Scott Gabree, Ph.D.
Stephanie Chase, Ph.D.
Kim Cardosi, Ph.D.



White Paper — June 2014

DOT-VNTSC-FAA-14-13
DOT/FAA/TC-14/18

Prepared for:
Federal Aviation Administration
Human Factors Division
Washington, DC 20591

U.S. Department of Transportation
Research and Innovative Technology Administration
John A. Volpe National Transportation Systems Center

Notice

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

U.S. Department of Transportation
Research and Innovative Technology Administration
John A. Volpe National Transportation Systems Center

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE June 2014	3. REPORT TYPE AND DATES COVERED Preliminary Draft Report

4. TITLE AND SUBTITLE Use of Color on Airport Moving Maps and Cockpit Displays of Traffic Information (CDTIs)	5a. FUNDING NUMBERS FAN2C2 KLA80
6. AUTHOR(S) Scott Gabree, Ph.D., Stephanie Chase, Ph.D. and Kim Cardosi, Ph.D.	5b. CONTRACT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation John A. Volpe National Transportation Systems Center Research and Innovative Technology Administration Cambridge, MA 02142-1093	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FAA-14-13
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Aviation Administration Human Factors Division 800 Independence Avenue, SW; Room 932 Washington, D.C. 20591 Program Managers: Colleen Donovan, Dr. Michelle Yeh, and Dr. Tom McCloy	10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FAA/TC-14/18
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE

13. ABSTRACT

Color can be an effective method for coding visual information, making it easier to find and identify symbols on a display (Christ, 1975). However, careful consideration should be given when applying color because excessive or inappropriate use of color can add confusion to an already complex display. A wealth of guidance exists for how to effectively use color in electronic displays, but it is spread across both Federal Aviation Administration (FAA) regulatory and guidance material and general human factors technical reports. Additionally, this information may not be presented in a way that clearly specifies how it can be applied to color use on an airport moving map or other avionics displays. The purpose of this document is to present known issues related to color which have been identified on current airport moving maps and Cockpit Displays of Traffic Information (CDTIs). This document also compiles FAA regulatory and guidance material, industry documents, and human factors research recommendations which address the use of color. Potential evaluation criteria for how an evaluator may assess the use of color on airport moving maps or other avionics displays are proposed.

14. SUBJECT TERMS Color, Airport Moving Map, Surface Moving Map, Human Factors, Symbols, Symbology, Traffic Display, CDTI, ADS-B, EFB, Cockpit Displays of Traffic Information	15. NUMBER OF PAGES 38
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Acknowledgments

This report was prepared by the Aviation Human Factors Division at the John A. Volpe National Transportation Systems Center (Volpe Center). This research was completed with funding from the Federal Aviation Administration (FAA) Human Factors Division (ANG-C1) in support of the Aircraft Certification Systems and Equipment Standards Branch (AIR-130) and Flight Technologies Requirements Branch (AFS-430). Thanks to our FAA program managers Colleen Donovan, Dr. Michelle Yeh, and Dr. Tom McCloy, and our FAA technical sponsors: Cathy Swider, Dr. Kathy Abbott, Don Walker, Usmaan Javed, and Paul VonHoene. We would also like to thank Dr. Robert (Buck) Joslin for his feedback on this report.

Feedback on this document may be sent to Scott Gabree (Scott.Gabree@dot.gov).

Contents

List of Figures **3**

List of Abbreviations **4**

Executive Summary **5**

1. Introduction **6**

2. Human Factors Color Issues **8**

2.1 Use of Red, Amber, and Yellow: Overuse or Inappropriate Use 9

Description of the Issue 9

FAA Regulatory and Guidance Material 9

Evaluation Considerations 11

2.2 Use of Blue: Difficulty Seeing Blue in Certain Settings 12

Description of the Issue 12

FAA Regulatory and Guidance Material 12

Industry and Research Recommendations 13

Evaluation Considerations 13

2.3 Consistency of Colors: Lack of Consistency with Color on Other Flight deck Displays 13

Description of the Issue 13

FAA Regulatory and Guidance Material 13

Evaluation Considerations 15

2.4 Redundant Use of Color: Lack of Redundant Coding 15

Description of the Issue 15

FAA Regulatory and Guidance Material 15

Evaluation Considerations 15

2.5 Color Discriminability/Symbol Discriminability and Distinctiveness: Traffic is Not Always Easy to See 16

Description of the Issue 16

FAA Regulatory and Guidance Material 17

Industry and Research Recommendations 19

Evaluation Considerations 21

2.6 Afterimages: Potential for Afterimages Following the Removal of a Color 21

Description of the Issue 21

Evaluation Considerations 22
2.7 Display Brightness: Appropriate Brightness for Ambient Lighting Conditions 22
Description of the Issue 22
FAA Regulatory and Guidance Material 23
Evaluation Considerations 25
3. References 26
Appendix A: CIE Color Space and its Transformations 29
Appendix B: Sources of Additional Information About Assessing Color with Dedicated Equipment 31

List of Figures

Figure 1. Photo Courtesy of ACSS (Excerpted from Yeh and Eon, 2009) 7

List of Abbreviations

Abbreviation	Term
AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance-Broadcast
AIAA	American Institute of Aeronautics and Astronautics
AMC	Acceptable Means of Compliance
AMMD	Aerodrome Moving Map Display
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CIE	International Commission on Illumination
CRT	Cathode Ray Tube
DOD	Department of Defense
EASA	European Aviation Safety Agency
EFB	Electronic Flight Bag
FAA	Federal Aviation Administration
GPS	Global Positioning System
HUD	Heads Up Display
ICAO	International Civil Aviation Organization
LCD	Liquid Crystal Display
LED	Light Emitting Diode
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NVG	Night Vision Goggles
NVIS	Night Vision Imaging System
TSO	Technical Standard Order
US	United States

Executive Summary

This report presents an overview of issues that have been identified involving the presentation of color on airport moving map and Cockpit Displays of Traffic Information (CDTIs). Color is often used on these displays with the intention of enabling pilots to more easily differentiate among the display elements depicted (e.g., runways, taxiways, gate areas, traffic aircraft, ownship, etc.). However, careful consideration should be given when applying color because excessive or inappropriate use of color can add confusion to an already complex display.

The Federal Aviation Administration (FAA) addresses the use of color in regulatory and guidance material, e.g., 14 CFR §25.1322, *Flightcrew Alerting*, AC 25-11A, *Electronic Flight Deck Displays,* and AC 25.1302-1, *Installed Systems and Equipment for Use by the Flightcrew.* Industry organizations and other research centers have also produced guidelines for color; for example, the NASA Ames Color Usage Research Lab identified 56 different documents that contain design recommendations for the selection and use of colors (NASA, 2004). Collectively, these documents provide a wide range of guidance for a variety of audiences with topics ranging from human factors considerations to more technical recommendations, such as accurately measuring color.

This document describes the following issues that have been identified in the use of color on airport moving map displays and CDTIs:

1) Use of Red, Amber, and Yellow: Overuse or Inappropriate Use;
2) Use of Blue: Difficulty Seeing Blue in Certain Settings;
3) Consistency of Colors: Lack of Consistency with Colors on Other Flight deck Displays;
4) Redundant Use of Color: Lack of Redundant Coding;
5) Color Discriminability: Traffic is Not Always Easy to Find;
6) Afterimages: Potential for Afterimages Following Color Removal; and
7) Display Brightness: Appropriate Brightness for Ambient Lighting Conditions

For each issue, applicable FAA regulatory and guidance material is presented. In addition, helpful guidance from research and industry are presented. Finally, assessment criteria that could be used to avoid or mitigate each issue are suggested. This document is intended to support a better understanding of the use of color on avionics displays and provide a summary of available guidance for the design and evaluation of the use of color on airport moving maps.

1. Introduction

When used appropriately, color is an effective method for coding visual information elements, making it easier to find and identify information on a display. The advantage of using color for search and identification tasks, when compared with a monochrome (i.e., grayscale) display, can be as much as a 200% increase in identification speed if the color of a target is unique for that target, and if that color is known in advance (Christ, 1975). Color can also help a user find and interpret complex information more quickly and accurately than on a monochrome display. However, careful consideration should be given when applying color to flight deck displays because color could further confuse an already complex environment if used inappropriately. This report will discuss issues concerning how color is used on avionics displays. The specific focus is the use of color on airport moving maps and CDTIs, but the issues described in this report are relevant to other avionics displays as well.

Airport moving maps and Cockpit Displays of Traffic Information (CDTIs) are examples of flight deck displays in which color is often used with the intention of helping the flightcrew find and interpret information. As can be seen in the example in Figure 1, these displays often depict a great deal of information. The airport surface is composed of several information elements (runways, taxiways, non-movement areas, etc.), depicted in various shades of gray. Runways are light gray and outlined in bright white. Ownship and traffic information are superimposed on the airport surface; ownship is depicted in magenta, and traffic aircraft are depicted as tan (if the aircraft is on the airport surface) or cyan (if the aircraft is in the air). Ownship and traffic aircraft information are dynamic, in that they move between runways, taxiways, and non-movement areas, and should remain visible to the flightcrew in all of these settings. The goal and challenge in designing and evaluating such a display is to ensure that the information elements are distinct and discriminable under all viewing conditions.

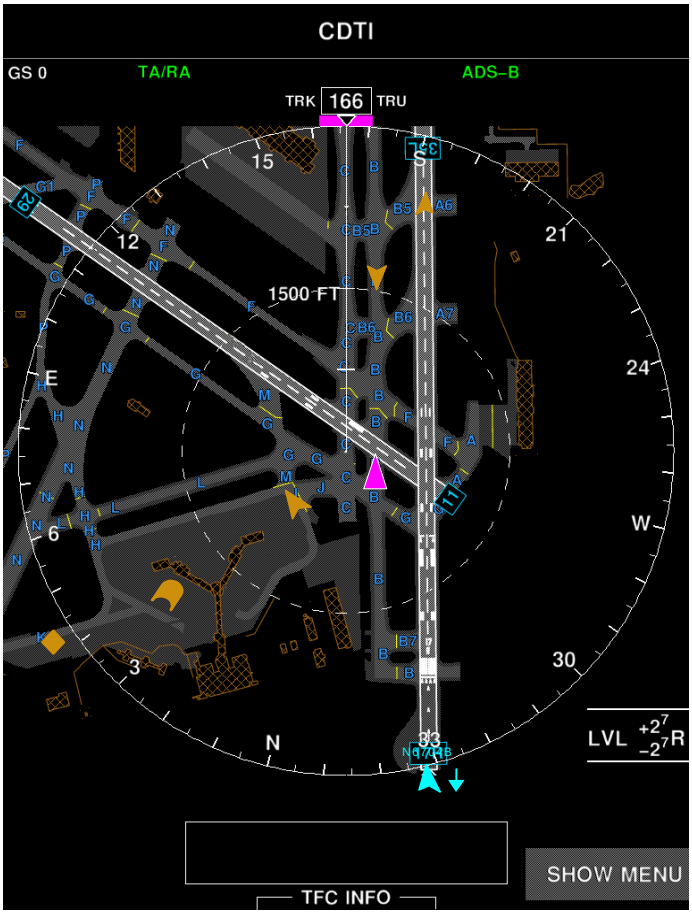


Figure 1. Photo Courtesy of ACSS (Excerpted from Yeh and Eon, 2009)

The Federal Aviation Administration (FAA) addresses the use of color in regulatory and guidance material, e.g., 14 CFR 25.1322, *Flightcrew Alerting*; AC 25-11A, *Electronic Flight Deck Displays*, AC 25.1302-1, *Installed Systems and Equipment for Use by the Flightcrew.* A comprehensive list of FAA regulatory and guidance material related to color can be found in a Volpe Center document, titled *Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls, Version 1.0*, which contains a section on color (Section 3.7). That document also contains recommendations from industry and research documents pertaining to the use of color in the flight deck. A wide range of guidance also exists for a variety of audiences with topics ranging from human factors considerations to more technical recommendations, such as accurately measuring color. The NASA Ames Color Usage Research Lab identified 56 different documents that contain design recommendations for the selection and display of colors (NASA, 2011). These documents are produced by a variety of organizations, including the FAA, American National Standards Institute/American Institute of Aeronautics and Astronautics (ANSI/AIAA), the American Society for Testing and Materials (ASTM), the U.S. Department of Defense (DoD), the International Commission on Illumination (CIE), the International Standards Organization (ISO), RTCA, European Aviation Safety Agency (EASA), and SAE. Despite this wealth of information, designers and evaluators of airport moving-maps may still have questions about how to apply color effectively, either because they are unaware of the available guidance or because it is not compiled into a single source document. Additionally, much of the guidance is quite technical and uses

terms (such as “chrominance”) can only be expected to be understood by those with an expertise in color.

The goal of this document is to offer guidance related to color issues that have been identified with airport moving map displays and CDTIs. The guidance comes from FAA regulatory and guidance material, industry documents, and general human factors research and is intended for use by display designers and evaluators. Possible evaluation criteria to use for avoiding or mitigating the issue are also included. Note that while the examples described specifically consider issues related to the use of color on airport moving map displays and CDTIs, the guidance is applicable to all avionics displays.

2. Human Factors Color Issues

This section describes seven key issues regarding the use of color on airport moving map displays and CDTIs. The seven issues are as follows:

- 2.1 Use of Red, Amber, and Yellow: Overuse or Inappropriate Use
- 2.2 Use of Blue: Difficulty Seeing Blue in Certain Settings
- 2.3 Consistency of Colors: Lack of Consistency with Color on Other Flight deck Displays
- 2.4 Redundant Use of Color: Lack of Redundant Coding
- 2.5 Color Discriminability/Symbol Discriminability and Distinctiveness: Traffic is Not Always Easy to See
- 2.6 Afterimages: Potential for Afterimages Following the Removal of a Color
- 2.7 Display Brightness: Appropriate Brightness for Ambient Lighting Conditions Appropriate Brightness for Ambient Lighting Conditions

Each issue contains a description of the problem as well as three pieces of information: (1) excerpts from relevant FAA Regulatory and Guidance material, (2) recommendations from industry documents and results of human factors research recommendations, and (3) evaluation considerations for how to avoid or mitigate the issue.

The source for the FAA Regulatory and Guidance Material is provided in brackets, immediately following the material. All *italicized* text is taken verbatim from the original source documents and is not altered or paraphrased. Additional related guidance follows the original source document. The words “shall”, “must”, or “should” appear here only if the words were in the original source document referenced in brackets. In these original source documents the term “shall” is used to indicate a minimum requirement, “must” is a requirement typically required by regulation, and “should” indicates a strong recommendation. This document is not intended to replace FAA regulatory and guidance material specific to the type of aircraft. Current FAA regulatory and guidance material takes precedence over the material here.

The source document for the Industry and Research Recommendations is also provided in brackets

following the italicized material. All *italicized* text is taken verbatim form the original source document and is not altered or paraphrased. Industry and Research Recommendations do not follow the same rules for the use of “shall”, “must”, and “should”, so all uses of these words in this section may be treated as recommendations of the source author(s).

It is important to note that the Evaluation Considerations are recommendations from the authors and are not regulatory; that is, compliance with these items is not mandated.

2.1 Use of Red, Amber, and Yellow: Overuse or Inappropriate Use

Description of the Issue

The use of the colors red and amber/yellow are to be reserved for warnings and cautions, respectively. However, these colors are sometimes considered for use on airport moving map displays in non-alert situations so that the color of the information on the display is identical to what the pilot would see out the window. The overuse of these colors (or colors that are confusable with these colors) in non-alerting situations may desensitize the crew to the urgency of alerts or distract the crew with a perceived alert where none is intended.

The following FAA guidance describes how the use of red, and amber/yellow should be addressed.

FAA Regulatory and Guidance Material

The use of red and amber/yellow for purposes other than warning and caution level alerting should be limited. Other uses have the potential to convey urgency where none exists and to reduce the attention-getting value of color-coded alerts.

- *Visual alert indications must:*
  - *(1) Conform to the following color convention:*
    - *(i) Red for warning alert indications.*
    - *(ii) Amber or yellow for caution alert indications.*
    - *(iii) Any color except red or green for advisory alert indications.*
  - (2) *Use visual coding techniques, together with other alerting function elements on the flight deck, to distinguish between warning, caution, and advisory alert indications, if they are presented on monochromatic displays that are not capable of conforming to the color convention in paragraph (e)(1) of this section.* [14 CFR §§ 25.1322 (e)]

  Related Guidance: 25.1322-1, Appendix 1, 2.c.; AC 120-76C; TSO-C113a, Appendix 1.1

- *If warning, caution, or advisory lights are installed in the cockpit, they must, unless otherwise*

approved by the Administrator, be -- [14 CFR 23.1322]

(a) Red, for warning lights (lights indicating a hazard which may require immediate corrective action);

(b) Amber, for caution lights (lights indicating the possible need for future corrective action);

(c) Green, for safe operation lights; and

(d) Any other color, including white, for lights not described in paragraphs (a) through (c) of this section, provided the color differs sufficiently from the colors prescribed in paragraphs (a) through (c) of this section to avoid possible confusion.

(e) Effective under all probable cockpit lighting conditions.

Related Guidance: 14 CFR 27.1322 and 29.1322 which are worded slightly differently; and AC 23.1322-1C, 22.7

- *Use of the colors red, amber, and yellow on the flight deck for functions other than flightcrew alerting must be limited and must not adversely affect flightcrew alerting.* [14 CFR 25.1322 (f)]

- *The applicant must limit the use of red, yellow, and amber for functions other than flightcrew alerting, so that misuse does not adversely affect flightcrew alerting per § 25.1322(f). Extensive use of red, yellow, and amber diminishes the attention-getting characteristics of warnings and cautions. This includes alert color consistency among propulsion, flight, navigation, and other displays and indications used on the flight deck.* [AC 25.1302-1, 5-5.b.(3)(b)]
  Related Guidance: AC 25.1322 – 1, 11.d

- *Displays must either conform to the alert color convention or, in the case of certain monochromatic displays not capable of conforming to the color conventions, use other visual coding techniques per § 25.1322(e). This is necessary so the flightcrew can easily distinguish the alert urgency under all foreseeable operating conditions, including conditions where multiple alerts are provided (§ 25.1322(a)(2)).* [AC 25.1322-1, 8.c.(3)]

- *Consistent use and standardization for red, amber, and yellow is required to retain the effectiveness of flightcrew alerts. It is important that the flightcrew does not become desensitized to the meaning and importance of color coding for alerts, which could increase the flightcrew's processing time, add to their workload, and increase the potential for flightcrew confusion or errors.* [AC 25.1322-1, 11.f]

- *Where red, amber and yellow are proposed for non-flightcrew alerting functions, substantiate that there is an operational need to use these colors to provide safety related awareness information. Examples of acceptable uses of red, amber, or yellow for non-alerting functions include:* [AC 25.1322 – 1, 11.g]

- *Weather radar display (for areas of severe/hazardous weather conditions that should be avoided);*
- *TAWS terrain display (for local terrain relative to the current altitude).*

- *The primary test for designation of color is:*
  (i) Red – Is immediate action required?
  (ii) Amber – Is pilot action (other than immediate) required?
  (iii) Green – Is safe operation indicated, and is the indication sufficiently distinct to prevent confusion with the landing gear down indication?
  (iv) *Other advisory lights – Is the meaning clear and distinct enough to prevent confusion with other annunciations? Do the colors which are utilized differ sufficiently from the colors specified above?* [AC 27-1B, AC 27.1322b(5)]

  Related Guidance: AC 27-1B CHG 3; AC 27.1322.b.(3); AC 29-2C; AC 29.1322a(6); AC 29.1322a(8)

- *The use of all colors must be consistent with commonly accepted aviation practice. The accepted practice for the use of red and amber is consistent with 14 CFR 25.1322 as follows* [TSO-C165/RTCA DO-257A 2.1.6.3]*:*
  - *Red shall be used only for indicating a hazard that may require immediate corrective action.*
  - *Amber shall be used only for indicating the possible need for future corrective action.*
  - *Any other color may be used for aspects not described in items a-b of this section, providing the color differs sufficiently from the colors prescribed in these items to avoid possible confusion.*

    <u>Notes:</u>
    - *Requirements a & b are intended to preclude the excessive use of amber & red on the AMMD. They are not meant to inhibit the use of red and amber for the coding of surface signs, lights, and markings.*
    - *These requirements are not intended to supersede system specific requirements in other avionics documents invoked by the FAA (e.g., TSO-C151b (TAWS), TSO-C119b (TCAS), AC 20-131A (TCASII)).*
    - *For Flight Information Service (FIS) overlays, the color guidelines of RTCA SC-195 apply. RTCA DO-267 is being updated by SC-195 including guidelines on the use of color.*

  Related Guidance: TSO-146c/RTCA DO-229D, 2.2.1.1.4.2

Evaluation Considerations

Ensure that red or amber/yellow are used appropriately and in compliance with the regulatory requirements in 14 CFR 25.1322, *Flightcrew Alerting*; there is related guidance that is worded differently in in 23.1322, 27.1322, and 29.1322. Any use of red or amber/yellow other than to convey a warning or caution, respectively, needs to be carefully assessed to ensure that the benefits outweigh the risks.

2.2 Use of Blue: Difficulty Seeing Blue in Certain Settings

Description of the Issue

The human eye processes color using three types of color-sensitive cells. One type color-sensitive cell responds best to blue light, another responds to red light, and the third responds to green light. The cells in the retina that respond best to blue lights are far fewer in number than those that respond best to green or red light. Additionally, the cells which respond best to blue light are absent from the central fovea (the very center of the eye), which is the part of the eye with the greatest acuity, used for reading and discerning fine details. Consequently, the color blue can be difficult to see on a dark background, especially when it is used to depict anything with fine details such as symbols or text. Legibility concerns with the color blue are most pronounced for “pure blue” which uses only the blue phosphors on the display. Blue phosphors are typically much lower in luminance than red or green phosphors, and this low luminance makes it especially difficult to read blue text or discern blue details when it is presented on a low luminance background, such as black or dark gray. Shades of blue that are easier to see than pure blue can be created by adding red or green pixels. Adding green pixels to pure blue creates cyan, which will have a higher contrast ratio against a dark background than will pure blue and thus will be easier to see. Another difficulty with blue is that it is at the far end of the visual spectrum, meaning that the eye may have difficulty focusing on blue at the same time as other colors, which will come into focus on different planes within the eye. For example, since red and blue are at opposite ends of the visual spectrum, when one color is in focus, the other will be slightly out of focus.

Issues with blue can be amplified as the eye ages and the often subtle changes in the aging eye may not be captured in routine color vision checks by aviation medical examiners. Age related effects are primarily driven by two factors. First, blue light is a short wavelength light that requires the eye to accommodate, or adjust its shape, to bring this light into focus. As the eye ages, it losses the ability to accommodate, making it more difficult to bring blue light into focus. This issue is especially problematic for small shapes which require more acute and detailed vision. Secondly, as the eye ages the lens of the eye yellows. This yellowing of the lens will cause blue light to appear more similar to white light. Each of these issues is important to consider for the wide range of ages that will be using the flight deck displays.

FAA Regulatory and Guidance Material

- *The use of pure blue should not be used for important information because it has low*

luminance on many display technologies (for example, CRT and LCD). [AC 25-11A, 31.c.(5)(i)]
Related Guidance: TSO-C146d, TSO-C165a/RTCA DO-257A, Appendix E E.3

- *Blue should be avoided because it is difficult for the human eye to bring blue symbols into focus and to distinguish the color from yellow when the symbols are small*. [TSO-C146d/RTCA DO-229D, 2.2.1.1.4.2]

- *Pure blue should not be used for the display of small, detailed symbols.* [TSO-C165/RTCA DO-257A, Appendix E.E.3]

- *Red and blue should not be presented adjacent to each other more than momentarily.* [TSO-C165a/RTCA DO-257A, Appendix E E.3]

Industry and Research Recommendations

- *Pure blue can also be mixed with green to create "cyan". While cyan is good for legibility, it can be confusable with blue, green, or white depending on how it is defined.* [Cardosi and Hannon, 1999, 3.1]

Evaluation Considerations

All uses of the color blue should be evaluated to make sure that they are legible. Specific consideration should be given to the use of blue against a dark background (in both day and night modes) or any use of blue to display text or symbols requiring fine discrimination. Any use of pure blue is especially likely to be problematic and thus should be carefully assessed.

2.3 Consistency of Colors: Lack of Consistency with Color on Other Flight deck Displays

Description of the Issue

Avionics displays on the flight deck should conform to the same color-coding philosophy. That is, colors that are assigned a meaning should be used consistently across all displays. For example, if there are two displays showing traffic information, the pilot could be confused if one display differentiates between airborne and ground traffic with a color change, but another display does not.

FAA Regulatory and Guidance Material

Using conventional color-coding schemes in the aviation community will help to keep color coding relatively consistent, such as defined in Table 11 and Table 12 of AC 25-11A. This way, the addition of a new display into the flight deck is less likely conflict with existing color schemes.

- *Aviation conventions should be observed when using colors for coding.* [TSO-C146d]
  Related Guidance: AC 25.1322-1, 10.a

- *To ensure correct information transfer, the consistent use and standardization of color is highly desirable. In order to avoid confusion or interpretation error, there should not be a change in how the color is perceived over all foreseeable conditions. Colors used for one purpose in one information set should not be used for an incompatible purpose that could create a misunderstanding within another information set. Inconsistencies in the use of color should be evaluated to ensure that they are not susceptible to confusion or errors, and do not adversely impact the intended function of the system(s) involved.* [AC 25-11A, 31.c.(5)(b)]
  Related Guidance: AC 25.1302-1, 5-5.b.(3)(c); AC 120-76C; AMC 25.1302, 5.4.2.d

- *A common color philosophy across the flightdeck is desirable, although deviations may be approved with acceptable justification.* [AC 25.1302-1, 5-5.b.(3)(a)]

- *Before defining the color standard for a specific display, establish a consistent color philosophy throughout the display.* [AC 23.1311-1C, 22.1]

- *Where appropriate, color assignment should be consistent with other color displays in the panel.* [AC 23.1311-1C, 22.5]

- *When overlaying two or more functions, using the same or similar color to convey different information is not recommended. If the same or similar colors are required, then retain the meaning of the different information.* [AC 23.1311-1C, 17.12.a]

- *Inconsistencies in the use of color should be evaluated to ensure that they are not susceptible to confusion or errors, and do not adversely impact the intended function of the system(s) involved.* [AC 25-11A, 31.c.(5)(b)]

- *The color-coding scheme employed for the airplane display should be evaluated for consistency with those recommended in AC 23.1311-1A. The effective use of color can greatly aid in pilot recognition and interpretation of displayed information. It is important that the use of color in all cockpit applications be consistent across all cockpit displays. The chosen colors should be evaluated to determine if they do in fact enhance the understanding of displayed information. Colors should minimize display interpretation errors.* [PS-ACE100-2001-004, Appendix A]

Evaluation Considerations

If multiple displays are used within a single flight deck, the evaluator should verify they do not have conflicting color-coding schemes. To ensure consistency, the evaluator should assess the entire color-coding scheme from every display used in the flight deck and make sure that they do not contradict one another. If any conflicts exist, then the evaluator needs to consider the potential impact of any misinterpretation or delays in interpretation.

2.4 Redundant Use of Color: Lack of Redundant Coding

Description of the Issue

Color is intended to complement and enhance the discriminability between symbols; it is not intended to be the only means available to differentiate between them. There are many reasons why using additional coding, such as shape, in addition to color ('redundant coding') is important. First, there are many degrees of color vision deficiencies. A pilot may have somewhat abnormal color vision, which results in seeing colors slightly different than someone with "normal" color vision, but not be diagnosed as "color blind." Second, even pilots with perfect color vision can have trouble differentiating colors due to environmental or display issues. Redundancy in coding provides an alternative means to differentiate among symbols.

The following FAA guidance describes how this issue should be addressed. The recommendations from industry and research are similar, and so are not repeated here.

FAA Regulatory and Guidance Material

- *Color is an enhancement for understanding the display information that leads to performance improvement, but it should not be the sole means of discrimination of critical information.* [AC 23.1311-1C, 22.6]
  Related Guidance: AC 20-175, 2-7.c; AC 25.1302-1, 5-5.b.(3)(d)

- *Color-coded information should be accompanied by another distinguishing characteristic such as shape, location, or text.* [TSO-C165/RTCA DO-257A, 2.1.6]
  See also: AMC 25.1302, 5.4.2; TSO-C113a/SAE AS8034B, 4.3.4; TSO-C146c/RTCA DO-229D, 2.2.1.1.4.2; RTCA DO-256, 2.1.3.6, which are worded slightly differently.

Evaluation Considerations

Evaluators should look at the full range symbols used to verify that every unique symbol differs from

every other symbol using a minimum of two coding parameters. An evaluator should be able to identify the meaning of each symbol when depicted in grayscale.

2.5 Color Discriminability/Symbol Discriminability and Distinctiveness: Traffic is Not Always Easy to See

Description of the Issue

How easy or difficult it is to see a symbol will depend on the contrast between the symbol and the background. This contrast depends on color as well as brightness; discriminability of a symbol is determined by the color difference and contrast ratio between the symbol and the background. The greater the contrast, the easier it will be to differentiate it from the background. If the colors of the symbol and the background area are too similar, or if the contrast ratio is too low, pilots might not be able to discern the symbol from its background or one color from another. One example of this issue is seen with the use of the colors tan and amber. The color amber/yellow is reserved primarily for caution level alerts. The color tan is often used to depict traffic on the ground. However, the colors tan and amber are chromatically similar. In fact, tan and brown are simply variants of yellow at low luminance; this means that it can be difficult to differentiate between tan and amber. Also, since tan is a low luminance color, it will be hard to pick out against a dark background. The contrast of dynamic symbols adds another level of complexity because a symbol that may be easily seen against one shade of gray (e.g., a light gray background) may not be as easily seen against another shade of gray (e.g., a darker gray) and vice versa. Thus, if runways are depicted in light gray and taxiways in dark gray, a tan symbol could be perceived to appear and disappear in different parts of the display. In addition, the implementation of alerts may also temporarily change the colors of the symbols or a portion of the airport surface, thereby changing the symbol/background combination.

Another important human performance issue is the ability to identify (as well as discriminate) colors on a display. Humans can discriminate among millions of colors; this means that we can determine whether or not there is a difference between two colors *when the colors are placed side by side*. The number of colors we can reliably *identify*, however, is closer to ten; when viewing conditions change, the number of reliably identifiable colors goes down to six. For example, if we took a box of 108 crayons and showed 'yellow-orange' and 'orange-yellow' side by side, most people would notice a distinct difference. If we showed only one of the 'yellow-orange' or 'orange-yellow' crayons, the chances of identifying it accurately would be close to 50%. If we asked people what color the crayon was in isolation, most would identify it as 'orange'. Colors that have been assigned a meaning (such as red for warning) need to be identifiable when presented alone on top of all anticipated backgrounds and viewing conditions.

Again, the similarity of colors can be objectively determined and specified in difference units. (See Appendix A for a complete discussion.) Each symbol needs to be discriminable against each possible background against which it could be displayed and at all expected luminance levels.

FAA Regulatory and Guidance Material

- *Each coded color should have sufficient chrominance separation so it is identifiable and distinguishable in all foreseeable lighting and operating conditions and when used with other colors. Colors should be identifiable and distinguishable across the range of information element size, shape, and movement. The colors available for coding from an electronic display system should be carefully selected to maximize their chrominance separation. Color combinations that are similar in luminance should be avoided (for example, Navy blue on black or yellow on white).* [AC 25-11A, 31.c.(5)(c)]
  Related Guidance: AC 23.1311 – 1C, 22.1; TSO-C113a/SAE AS8034B, 4.3.3; SAE ARP4032B; Specific color pairs to avoid can be found in AC 25-11A, 31.c.(5)(g).

The selection of the background color for a display is as important as the selection of the colors to be used for the information presented. Some airport moving maps use a black or dark green background, and these colors generally provide good contrast when overlaying other airport information elements (e.g., runways, taxiways, and non-movement areas, which are often depicted in various shades of gray).

- *When background color is used (for example, gray), it should not impair the use of the overlaid information elements. Labels, display-based controls, menus, symbols, and graphics should all remain identifiable and distinguishable. The use of background color should conform to the overall flight deck philosophies for color usage and information management. If texturing is used to create a background, it should not result in loss of readability of the symbols overlaid on it, nor should it increase visual clutter or pilot information access time. Transparency is a means of seeing a background information element through a foreground one – the use of transparency should be minimized because it may increase pilot interpretation time or errors.* [AC 25-11A, 31.c.(5)(h)]
  Related Guidance: TSO-C113a, Appendix 1.2

Overlaid information can also become difficult to interpret if colors that are too similar to one another are used to convey different meanings.

- *When overlaying two or more functions, using the same or similar color to convey different information is not recommended. If the same or similar colors are required, then retain the meaning of the different information.* [AC 23.1311-1C, 17.12.a]

Limiting the number of color codes will help pilots distinguish among all of the colors used and to remember the meanings affiliated with each color.

- *No more than six colors should be used for color-coding on the display.* [TSO-C165a/RTCA DO-257A, 2.1.6]
  Notes:

- *Use of additional colors for other purposes should not detract from the discriminability of colors used for coding.* [TSO-C165a/RTCA DO-257A, 2.1.6]
- *This restriction on the number of colors may not apply to information shared with the Electronic Map Display such as terrain and weather.* [TSO-C165a/RTCA DO-257A, 2.1.6]

Related Guidance: AC 25-11A, 31.c.(5)(c); RTCA DO-256, 2.1.3.6; TSO-C113a/AS8034B, 4.3.3; SAE ARP4032B, 4.2.2.1.

- Avoid using many different colors to convey meaning on displays. If thoughtfully used, however, color can be very effective in minimizing display interpretation workload and response time. Color can be used to group logical electronic display functions or data types. A common color philosophy across the flightdeck is desirable, although deviations may be approved with acceptable justification. Information for color coding on flightdeck electronic displays is provided in AC 25-11A, Electronic Flight Control Displays. [AC 25.1302-1, 5-5.b.(3)(a)]
  Related Guidance: AMC 25.1302, 5.4.2.d

In some cases color may not be used directly for color coding, but rather for representing the outside world or to depict terrain or weather features. If color is used not for coding, but to represent the outside world in some way, the use of more than six distinct colors may be warranted (e.g., as a hierarchical set of colors depicting different elevations) so long as it does not interfere with the pilot's ability to see any overlaid information.

- *Other graphic depictions such as terrain maps and synthetic vision presentations may use more than six colors and use color blending techniques to represent colors in the outside world or to emphasize the terrain features. These displays are often presented as background imagery and the colors used in the displays should not interfere with the flightcrew interpretation of overlaid information parameters.* [AC 25-11A, 31.c.(5)(d)]

Not only should the colors and chrominance separation (color difference) between an information element and its background be considered, but also the luminance (or brightness) contrast. Two colors, even colors which may seem very different, can often be difficult to distinguish when they are displayed at the same luminance. For example, darkening a tan color to brown will reduce its similarity to amber, but will be difficult to see against a dark background.

- *Adjacent colors should not be equal in luminance when discrimination of edges or detail is important.* [TSO-C165a/RTCA DO-257A, Appendix E E.3]

The appearance of a color on a display will vary depending on the display being used. Color differences may be especially large if different display technologies are used, e.g., a CRT vs. LCD vs. LED display. However, even similar hardware (e.g., LCD displays) from two different manufacturers may differ, even if they are both using the same software and color scheme. This

means that assessments are not interchangeable between different presentations of the same information, as the precise appearance of a color cannot be assessed without both the hardware and software which will be used in the flight deck.

- *Evaluations should also verify the chromaticity (red looks red and amber looks amber) and discriminability (colors can be distinguished from each other) of the colors being used, under the expected lighting levels. Evaluations may also be useful to verify the discriminability of graphic coding used on monochromatic displays. These evaluations can be affected by the specific display technology being used, so a final evaluation with production representative hardware is sometimes needed.* [AC 25.1322-1, 13.c.(4)]
  Related Guidance: PS-ACE100-2001-004, Appendix A; PS-ANM-01-03A, Appendix A, 3

Industry and Research Recommendations

Cardosi and Hannon (1999) provide guidance for which six colors will be maximally discriminable on a Cathode Ray Tube (CRT) type of display. Though CRTs are used less frequently today, and have been replaced by Liquid Crystal Displays (LCDs) and Light-Emitting Diode (LED) displays, the same colors are likely to provide a maximally discriminable color-coding set.

- *The six colors that are maximally discriminable on a CRT are:*
  - *Red,*
  - *green,*
  - *blue,*
  - *yellow,*
  - *cyan, and*
  - *magenta.*

  In addition the color set could include (depending on the background) the achromatic colors of:
  - *Black,*
  - *grey, and*
  - *white.* [Cardosi and Hannon, 1999, 3.4]

All colors can be plotted in color space and specified using CIE L*u*v coordinates. Detailed information about color spaces and objective color measurement techniques and tools is provided in Appendix A. If any colors are too similar to ones that have been assigned a meaning ('reserved colors'), such as red or amber/yellow, they have the potential to reduce the perceived urgency of real alerts. In order to objectively determine the similarity of colors, difference units can be computed. MIL-STD-1472G, 5.2.2.3.1.o specifies that "*Colors in a set shall differ from one another by not less than 20 D E (CIE L*u*v) distances."* The document also describes how one can calculate the difference between two colors.

- *Colours should not just be assessed subjectively (depending on the assessment of the*

observer: response of the type: "it's red; it's pink; it's violet…"), as the variability and scatter of opinions is too great. They have to be measured and quantified using a metric developed by the Commission Internationale de l'Eclairage (CIE) also known as the International Commission on Illumination (ICI), which is illustrated in Figure 1.1. This enables measurement within a standardized scale representing all colours used, and after photocolourimetric measurements, the trichromatic coordinates x and y are defined, as well as the luminance expressed in candela per square metre. [RTO-TR-016, AC/323(HFM-012)TP/6, 1.3]

If a color is being used to code a particular meaning, the flightcrew should easily be able to identify the color when presented alone, not just when there are other colors to compare it to.

- *When colors are assigned a meaning, such as… yellow for "caution", the colors should be readily identifiable and each color should have only one meaning. This means that colors assigned a meaning should be able to be identified with near 100% accuracy, no matter which other color is present (or not present) in the display.* [Cardosi and Hannon, 1999, 3.1]

Both color and luminance contrast are important in determining if an information element is distinct from the background. For example, a low luminance color such as dark blue is difficult to see against a low luminance background such as black, because the luminance contrast ratio is very low. The ratios recommended by Cardosi and Hannon are intended for an aviation setting. It is worth noting that the contrast ratios are greater than those set forth by the American National Standards Institute (ANSI)[1], but the ANSI standards were intended for displays used in an office.

- *When selecting colors for a display, it is important to consider the chromatic and luminance contrast that particular colors (foreground and background) will yield. Contrast is a key factor in determining whether or not items on a display will be legible. For items that need to be read, such as data blocks, a contrast of 8:1 is recommended (but not necessary) to ensure legibility. For details that do not need to be read, such as maps and range rings, a contrast ratio of 3:1 (sometimes less) is acceptable. These guidelines, originally developed by ICAO (1993), are sound principles that ensure legibility.* [Cardosi and Hannon, 1999, 3.1]

The size of a symbol will affect the ability to identify the color. Furthermore, some colors are more affected than others. For example, it is very difficult to tell the difference between white and yellow text or symbols; red and green are not as easily affected. If the symbols being color coded are too small, the flightcrew may not be able to easily identify the colors, and thus the meanings of the symbols on the screen.

- *Color symbols must be larger if color coding is important. Studies have shown the need for larger symbols to allow color identification among six possible colors*. [MIL-HDBK-87213, 3.2.1.3.1 e]

[1] ANSI (2007) recommends that contrast ratios on a display be at least 3 to 1 and, if luminance is used to code information, then the codes should differ by a ratio of at least 1.5 to 1.

In order to ensure that a symbol (or other information element) can be discriminated from the background, an evaluator may choose to use an objective measure, such as the distance between two colors in the CIE L*u*v color space. Each possible symbol/background combination can be compared to ensure that they are different enough from one another to be distinguished. More detailed information about CIE color spaces and additional sources to learn more about how to use these color spaces are provided in Appendix A and Appendix B, respectively. Additionally, the section of MIL-STD-1472G that is quoted below continues on to detail specific equations that are used to derive this guidance and should be referenced for a better understanding of how to use this information.

- *Colored symbols shall differ from their background by not less than 100 D E (CIE L*u*v) distances.* [MIL-STD-1472G, 5.2.2.3.1.n]

Evaluation Considerations

Evaluate each of the symbol/background combinations, including indications and alerts, using the display technology on which they will be presented in the following conditions:

- the full range of backgrounds on which each symbol will be presented
- in day and night mode
- under the full range of daytime and nighttime lighting conditions.

The FAA does not prescribe one specific way to ensure that the colors chosen are adequately discriminable. However, as previously discussed, objective measures for determining that colors are sufficiently different, both from other colors used on the display and from the background, are discussed in detail in Appendix A. Specifically, colors can be plotted in the CIE L*u*v color to ensure that no colors are too close (e.g., a distance of 20 D E as defined in MIL-STD-1472G) to the red and amber/yellow colors being used for alerting, and a difference of 100 D E to be differentiable from the background.

2.6 Afterimages: Potential for Afterimages Following the Removal of a Color

Description of the Issue

An afterimage is an illusory perception of a color that persists after the removal of that color from the display (Wade, 2000). Afterimages are created in the retina of the eye and are particularly noticeable when a bright color is removed after focusing on it. The color of the afterimage appears as the perceptual opposite of the color which was previously on the display; e.g., the removal of a green

stimulus (such as when transitioning from Night Vision Goggles (NVGs) or a green Heads Up Display (HUD)) will result in a red or magenta afterimage, the removal of a red stimulus will result in a green afterimage, and the removal of a blue stimulus will result in a yellow afterimage. For example, if an airport moving map uses a blue outline to highlight a runway when it is in use, the removal of the blue outline may cause the flightcrew to perceive a yellow afterimage (a yellow outline surrounding the runway). Afterimages will move as the eye moves, so if the pilot shifts his/her gaze away from the display the afterimage will no longer appear in the same location. However, afterimages can be vivid (and therefore distracting) if the display is bright or if the pilot spends a significant amount of time focusing on the display.

Currently, there is no specific guidance to directly address afterimages. However, it is possible to evaluate the potential effects of afterimages in the flight deck.

Evaluation Considerations

Afterimages are most likely to occur immediately following the removal of a color from the screen (e.g., following the resolution of an alert or warning situation or a change in status of some symbols). The evaluator should identify and assess operational scenarios likely to create afterimages.

2.7 Display Brightness: Appropriate Brightness for Ambient Lighting Conditions

Description of the Issue

Ambient illumination plays an important role in the appearance of information on the display. Direct sunlight can 'wash out' a display, making it difficult to see, due to the reduced contrast. (Wearing sunglasses will further reduce the contrast.) This is an important consideration for display placement on the flight deck. Other visual enhancements, such as Night Vision Imaging Systems (NVIS) can also greatly impact color and luminance perception, but are not the focus of this document. For guidance about the interactions between NVIS and electronic displays see RTCA/DO-275, *Minimum Operating Performance Standards for Integrated Night Imaging System Equipment*.

At night, pilots require a darker flight deck environment so they can see both inside the flight deck and out the window. The human visual system adapts to the environmental lighting; that is, if the pilot is in a dark environment, the visual system will slowly adjust so that it can more easily see in that dark environment, and vice versa. However, the human visual system does not transition quickly between very dark and very bright environments, and even brief exposure to a bright light source can disturb dark adaptation and make it temporarily difficult to see in the dark. If dark adaptation is disturbed, it can take anywhere from several minutes to up to 30 minutes to fully recover, depending on the brightness and duration of the light that disturbed the adaptation (Pirenne, 1962). A dimming capability for

avionics displays is needed to adjust the brightness of the display to prevent such drastic jumps in brightness.

Some flight deck equipment may have a dedicated "night mode" for use during night flight. In night mode, the background of the display is typically dark to minimize the amount of brightness being produced by the display, such as white runways on a black background instead of black runways on a white background. Since the background typically encompasses the majority of the display, having a black background helps to reduce the brightness of the display and thus the overall brightness in the flight deck. However, as the pilot changes the map range to zoom in closer to the airport surface, the relative amount of background, and the "darkness", decreases since the runways, taxiways, and other information elements increase in size and occupy more space on the display. In this case, the night mode may actually produce a *brighter* display image than the day mode would have. Quick changes in the brightness of the display, which could be brought on by large changes in the zoom level, may have the potential to disturb the dark adaptation of the flightcrew and make it difficult for them to see anything out the window at night.

FAA Regulatory and Guidance Material

A pilot will not be able to use the same brightness levels during each phase of flight; a dim display will be unreadable in bright sunlit conditions and a bright display will disturb dark adaptation during night flight. Displays are required to be tested under this range of lighting conditions to ensure that the range of brightness settings available can accommodate all types of environmental conditions.

- *Each pilot compartment must be free of glare and reflection that could interfere with the normal duties of the minimum flight crew. This must be shown in day and night flight tests under nonprecipitation conditions.* [14 CFR 25.773(a)(2)]
  Related Guidance: 14 CFR 23.773(a)(2), 27.773(a)(2), and 29.773(a)(2); and see also PS-ACE100-2001-004, Appendix A

Having a very bright display can be helpful in a *bright* flight deck environment. However, if the display is too bright, particularly in a *dark* flight deck environment, it may negatively impact the pilot's ability to see other displays in the flight deck.

- *Display luminance shall not interfere with the usability of other flight deck displays nor produce unacceptable glare against the windscreen or other reflective surface.* [TSO-C165a/RTCA DO-257A, 3.1.3.2]

Many avionics displays have the capability of switching between "day" (bright background) and "night" (dark background) modes. These two modes have drastically different background colors, so symbols that are overlaid on these backgrounds need to have a high color and

luminance contrast ratio in both modes. Since pilots will be flying under a wide variety of lighting conditions, it is important to make sure that the colors are identifiable and discriminable across all lighting conditions and display modes.

- *Colors should track brightness so that chrominance and relative chrominance separation are maintained as much as possible during day-night operations.* [TSO-C113a, Appendix 1. 3]

- *Luminance and color differences should not be confusing or ambiguous under any operating ambient illumination conditions. The specific colors should be consistent with change in brightness on the displays over the full range of ambient light conditions. [AC 23.1311-1C, 22.5]*

- *Displayed information shall have sufficient luminance contrast and/or color difference to discriminate between the following as applicable: [TSO-C113a/SAE AS8034B, 4.3.3]*
  a. *Between symbols* (including characters and/or lines) and the background (ambient or generated) on which they are overlayed.
  b. *Between* various symbols, characters and lines. This shall also include when they overlay ambient or generated backgrounds.
  c. *Between* the generated backgrounds and ambient backgrounds.
  d. *Between* the generated backgrounds of various specified colors.

- *In all cases the luminance contrast and/or color differences between all symbols, characters, lines, or all backgrounds shall be sufficient to preclude confusion or ambiguity as to information content of any displayed information. When operationally relevant, the color of the information shall be identifiable (e.g., if colors are used for alerting). The manufacturers shall specify the ambient illumination level and illuminate characteristic for which this requirement is met.*
  Note: It is not recommended to place a symbol on a background of equal luminance regardless of color differences. Saturated colors are not recommended to be used for background; saturated colors should be saved for smaller items such as symbols, icons, targets, etc. [TSO-C113a/SAE AS8034B, 4.3.3]

- *Displays shall be readable and colors shall be discernable under anticipated lighting conditions.* [TSO-C146c/RTCA DO-229D, 2.2.1.1.4.2]

- *Each coded color should have sufficient chrominance separation so it is identifiable and distinguishable in all foreseeable lighting and operating conditions and when used with other colors. Colors should be identifiable and distinguishable across the range of information element size, shape, and movement. The colors available for coding from an electronic display system should be carefully selected to maximize their chrominance separation. Color combinations that are similar in luminance should be avoided (for example, Navy blue on*

back or yellow on white). [AC 25-11A, 31.c.(5)(c)]
See also: SAE ARP4032B

- *Requiring the flightcrew to discriminate between shades of the same color for distinct meaning is not recommended.* [AC 25-11A, 31.c.(5)(i)]

- *Adjacent colors should not be equal in luminance when discrimination of edges or detail is important.* [TSO-C165/RTCA DO-257A, Appendix E E.3]

Evaluation Considerations

Consider color visibility under the full range of ambient illumination in both day and night operating environments. The evaluator should verify that the display can be accurately seen in both bright sunlight and in a dimly lit flight deck environment. When assessing readability in a dimly lit flight deck, the evaluator must also consider the impact of the display on dark adaptation. A pilot will become dark adapted over a period of approximately 10 to 30 minutes, so any evaluations of disturbances to dark adaptation must be conducted after this adaptation period has passed (Davson, 1990). The impact of disturbances to dark adaptation will depend on the intensity and length of exposure of the disturbing light, but any disturbances in dark adaptation should be followed by another adaptation period to re-acclimate to the dark environment. Night mode settings should be dim enough across all zoom levels to *not* disturb the dark adaptation of the pilot. For most night mode settings, the display is brightest, and most disruptive, when the most amount of information is being depicted relative to the background – e.g., when the display is zoomed in close to the airport surface. The evaluator should assess if, while in night mode, the display can become so bright that it will disrupt the flight crew's dark adaptation.

3. References

FAA Regulatory and Guidance Material

Federal Aviation Administration, Advisory Circular (AC) 23.1311-1C, Installation of Electronic Display in Part 23 Airplanes. November 17, 2011.

Federal Aviation Administration, Advisory Circular (AC) 25-11A, Electronic Flight Deck Displays. June 21, 2007.

Federal Aviation Administration, Advisory Circular (AC) 25.1302-1, Installed Systems and Equipment for Use by the Flightcrew. May 3, 2013.

Federal Aviation Administration, Advisory Circular (AC) 25.1322, Flightcrew Alerting. December 13, 2010.

Federal Aviation Administration, Advisory Circular (AC) 120-76B Guidelines for the certification, airworthiness, and operational approval of electronic flight bag computing devices, June 1, 2012.

Federal Aviation Administration, Technical Standard Order (TSO)-C113a, Airborne Multipurpose Electronic Displays, April 30, 2012

Federal Aviation Administration, Technical Standard Order (TSO)-C146d Stand-Alone Airborne Navigation Equipment Using The Global Positioning System Augmented By The Satellite Based Augmentation System, December, 20, 2013.

Federal Aviation Administration, Technical Standard Order (TSO)-C165a, Electronic Map Display Equipment for Graphical Depiction of Aircraft Position, September 30, 2013

Title 14 of the Code of Federal Regulations (CFR) 23.1322, *Warning, caution, and advisory lights.*

Title 14 of the Code of Federal Regulations (CFR) 25.1322, *Flightcrew Alerting.*

Title 14 of the Code of Federal Regulations (CFR) 27.1322, *Warning, caution, and advisory lights.*

Title 14 of the Code of Federal Regulations (CFR) 29.1322, *Warning, caution, and advisory lights.*

Military Documents

Military Standard (MIL-STD) 1472G, (2012), *Department of Defense Design Criteria Standard: Human Engineering*. Washington, DC: U.S. Department of Defense.

Military Handbook (MIL-HDBK) 87213A (2005). *Department of Defense Handbook: Electronically/Optically Generated Airborne Displays.* Washington, DC: U.S. Department of Defense.

SAE and ASTM Documents

American Society for Testing and Materials (ASTM) E1455 – 03. *Standard Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimiters.* 2010.

Society of Automotive Engineers (SAE) ARP4038B, *Human Engineering Considerations in the Application of Color to Electronic Aircraft*. March, 2013.

Society of Automotive Engineers (SAE) ARP4256, *Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft*. December, 2001.

Society of Automotive Engineers (SAE) ARP4260A: *Photometric and Colorimetric Measurement Procedures for Airborne Flat Panel Displays.* April 22, 2009.

Society of Automotive Engineers (SAE) AD50083: *Human Factors Issues Associated with Cockpit Display of Traffic Information (CDTI)*. December, 1999.

RTCA, Inc. Documents

RTCA DO-229D, *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*. December 13, 2006.

RTCA DO-256, *Minimum Human Factors Standards for Air Traffic Services Provided via Data Communications Utilizing the ATN, Builds 1 and 1A*. June 20, 2000.

RTCA DO-257A, *Minimum Operational Performance Standards for the Depiction of Navigational Information on Electronic Maps.* June 25, 2003.

RTCA DO-275, *Minimum Operational Performance Standards for Integrated Night Vision Imaging System Equipment. October 12*, 2001.

Volpe Center EFB Research Reports

The following documents are available at www.volpe.dot.gov/our-work/safety-management-and-human-factors/human-factors-publications-and-papers.

Cardosi K., & Hannon, D. (1999). Guidelines for the use of color in ATC displays. Washington, DC: Federal Aviation Administration; No: DOT/FAA/AR-99/52.

Yeh, M. and Eon, D. (2009). Surface Moving Map Industry Survey (DOT-VNTSC-FAA-09-15). Cambridge, MA.

Yeh, M, Young, J., Donovan, C., & Gabree, S. (2013).Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls Version 1.0 (DOT/FAA/TC-13/44 DOT-VNTSC-FAA-13-09)

Other Research Reports

European Aviation Safety Agency, 2007a. Certification Specifications for Large Aeroplanes CS-25 Amendment-3, Book 2, Acceptable Means of Compliance, Subpart F Equipment, General, AMC 25.1302 Installed systems and equipment for use by the flight crew, September 19, 2007.

ANSI/HFES 100-2007. (2007). Human Factors Engineering of Computer Workstations.

Avionics Systems Harmonization Working Group, Flight Crew Alerting (Final Version FAR/JAR 25.1322 & AC/ACJ 25.1322), May 14, 2004

Christ, R. E. (1975). Review and analysis of color coding research for visual displays. Human Factors, 17, 542-570.

Davson H. (1990) *Physiology of the Eye, 5th ed*. London: Macmillan Academic and Professional Ltd.

NASA Color usage website: http://alexlogan.com/nasa/guidelines_specific.html

Operational color vision in the modern aviation environment. RTO Technical Reports, RTO-TR-016 AC/323(HFM-012)TP/6.

Pirenne M.H. (1962) Dark Adaptation and Night Vision. Chapter 5. In: Davson, H. (ed), *The Eye, vol 2*. London, Academic Press.

Public Statement Number PS-ACE100-2001-004, Guidance for Reviewing Certification Plans to Address Human Factors for Certification of Part 23 Small Airplanes, August 29, 2002

Schanda, J. (2007). Colorimetry. New York: John Wiley and Sons, Inc.

Wade, N. J. (2000). A natural history of vision. MIT Press.

Xing, J. (2006). Color and Visual Factors in ATC Displays. (DOT-FAA-AM-06/15). Oklahoma City, OK.

Yeh, M., & Wickens, C. D. (2001). Attentional filtering in the design of electronic map displays: A comparison of color coding, intensity coding, and decluttering techniques. Human Factors: The Journal of the Human Factors and Ergonomics Society, 43(4), 543-562.

Appendix A: CIE Color Space and its Transformations

The International Commission on Illumination – or Commission Internationale de L'Eclairage (CIE) – is an international authority that has developed standards to quantify illumination, color, and color spaces. A color space is a way in which colors can be represented in a quantitative way and mapped to show each color's position relative to other colors. When a measurement is taken with a piece of equipment that is designed to measure color, it will return a series of values that represent a "location" in a color space. The output of the equipment's measurement can be one of a variety of different outputs.

"RGB" is one type of color space. An RGB value specifies the amount of red (R), green (G), and blue (B) required to create a certain color on a display screen. To display a color on a computer screen, the graphics software specifies a value for R, G, and B between 0 (lowest intensity) and 255 (highest intensity). For example, black is represented by the RGB value (0, 0, 0), white is (255, 255, 255), and pure blue is (0, 0, 255). It is possible to calculate contrast ratios between an information element and a background using these values (see Appendix B of Xing, J., 2006). However, colors as represented by RGB space heavily depend on the display screen being used. To more accurately measure colors on a display screen, a color measurement method that is independent of the display technology is required. One way to accomplish this is to measure colors and plot them in the CIE XYZ color space.

The 1931 CIE XYZ color space can be transformed from the RGB color space via a 3x3 matrix transform. XYZ measures the physical properties of color and light, not the properties of the display producing the color; thus, the CIE XYZ values are considered to be display-independent.

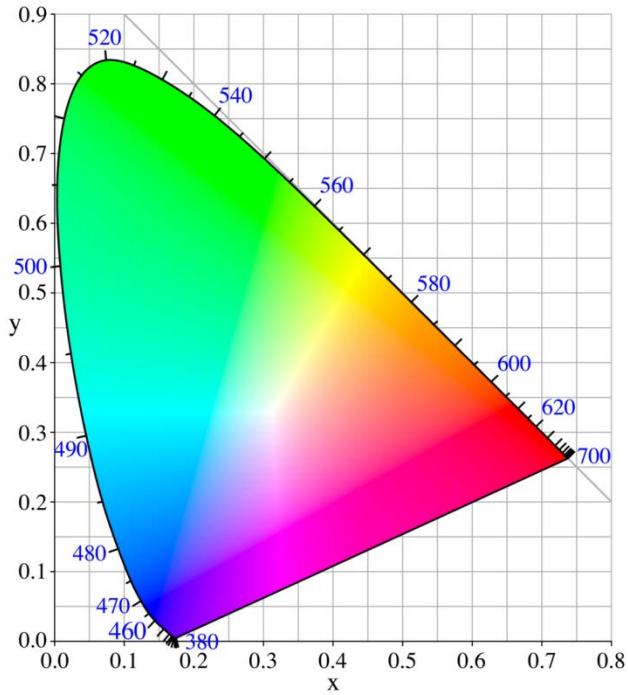


Figure 2. CIE 1931 XYZ Color Space

Spectrophotometers measure color using *x, y*, and *z* coordinates, which correspond to a location in CIE XYZ color space. The issue with this color space, especially when attempting to determine how perceptually similar or distinct two colors are (i.e., are the colors chosen to code information elements distinct enough from one another), is that greater distances between two points in CIE XYZ space do not necessarily translate into greater perceptual differences.

To account for this, CIE developed a transformation from XYZ to another color space, named CIELUV, in an attempt at "perceptual uniformity." A perceptually uniform color space would be one in which the Euclidean distance between two color values in the color space directly represents how similar or different those two colors are perceived. Two color values that are close together at any location in this space would be similar in appearance and, as the values moved further apart in any direction, they would appear less and less similar. CIELUV color space does not use *x, y,* and *z* values like CIE, but instead uses L' (luminance), *u'* (adjusted *x* value), and *v'* (adjusted *y* value). The distance between two colors in this color space is referred to as DLuv*. If measurements are taken using the L', *u', v'* values and plotted in CIELUV space, it may be easier to determine if the colors being used are distinct enough from one another to be discriminated easily. In 2007 the American National Standards Institute (ANSI) approved the ANSI/HFES 100-2007, *Human Factors Engineering of Computer Workstations.* Though intended for office workstations and not an aviation setting, this document recommends a color difference (DLuv*) greater than 20 to ensure color discriminability.

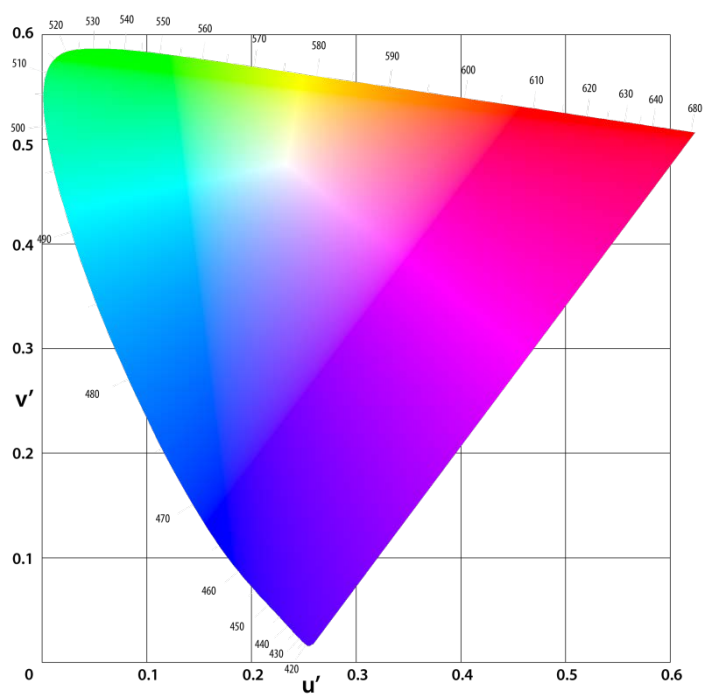


Figure 3. CIE LUV Color Space

Appendix B: Sources of Additional Information About Assessing Color with Dedicated Equipment

This appendix lists additional references which may be helpful when evaluating colors on an airport moving map using spectrophotometers and other specialized equipment to measure color and luminance. There are three main sections:

1. Measurement Tools and Techniques – References that provide information about the equipment which can be used in a color evaluation or guidelines for using or calibrating this equipment.
2. Basics of Color Science – References that provide background information about color science in general. This section also includes references to papers and books which provide a more in depth understanding of color spaces.
3. Color of Luminance Standards – References that provide recommendations for minimum/maximum values for color, luminance, or contrast.

Measurement Tools and Techniques

ASTM E308-06, *Standard practice for computing the color of objects by using the CIE system*.

ASTM E1336-91, *Standard Test Method for Obtaining Colorimetric Data from a Visual Display Unit by Spectroradiometry.*

ASTM E1341, *Practice for Obtaining Spectroradiometric Data from Radient Sources for Colorimetry.*

ASTM E1455-92, *Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters.*

ASTM E1682 – 08, *Standard Guide for Modeling the Colorimetric Properties of a CRT-Type Visual Display Unit*

Brown, S. & Ohno, Y. (1998). *NIST Reference Spectroradiometer for Color Display Calibrations*. Proc IS&T Sixth Color Imaging Conference.

SAE ARP4260A, *Photometric and Colorimetric Measurement Procedures for Airborne Flat Panel Displays*

Title 14 of the Code of Federal Regulations (CFR) Part 67.303, *Eye.*

Ohno, Y. & Hardis, J. (1997). *Four-Color Matrix Method for Correction of Tristimulus Colorimeters*. Proc. IS&T Fifth Color Imaging Conference.

Basics of Color Science

Boynton RM, Olson CX (1990). *Salience of chromatic basic color terms confirmed by three measures*. Vision Res; 30(9): 1311-7.

CIE (1931). Proceedings of the 8th Session, International Commission on Illumination, pp: 19-29. Bureau Central de la CIE, Paris.

CIE No. 15.2 (1986). Colorimetry, 2nd ed., Commission Internationale de 1'Eclairage, Vienna, Austria.

NASA Color Usage Webpage (2004). http://colorusage. arc.nasa.gov (Internet address as of September, 2012).

CIE (1991). Standard Colorimetric Observers, ISO/CIE 10527.

International Organization for Standardization. (2007). *Colorimetry – Part 1: CIE standard colorimetric observers* (ISO 11664-1:2007).

International Organization for Standardization. (2007). *Colorimetry - Part 2: CIE standard illuminants* (ISO 11664-2:2007).

Fairchild, M. D. (2005). *Color appearance models (2nd ed.)*. Hoboken, NJ: J. Wiley.

Wandell, B. (1996). The Foundations of Color Measurement and Color Perception. SIC Seminar Lecture Notes, 1991. http://white.stanford.edu/~brian/papers/ise/sid-colornotes.pdf

Wyszecki G, Fielder GH (1971). *New color-matching ellipses*. J Opt Soc Am A; 61(9): 1135-52.

Wyszecki, G., & Stiles, W. S. (1982). *Color Science*. John Wiley and Sons, New York. Second Edition.

Color or Luminance Standards

ASTM International Standard on Color and Appearance Measurement (8th ed.) [CD-ROM]. West Conshohocken, PA: ASTM.

Federal Aviation Administration (2003). *Human factors design standard HF-STD-001*. Washington, DC: Federal Aviation Administration. Available for download at http://hf.tc.faa.gov/hfds.

Federal Aviation Administration (2007). *Baseline Requirements for Color Use in Air Traffic Control Displays HF-STD-002*. Washington, DC: Federal Aviation Administration.

Ferne, F, Allendoerfer, K., & Pai, S. (2008). *Air Traffic Control Display Standard: A Standardized Color Palette for Terminal Situation Displays*. (DOT/FAA/TC-18/15) Atlantic City, NJ.

Squire, T. J., Rodriguez-Carmona, M., Evans, A. D., & Barbur, J. L. (2005). Color vision tests for aviation: comparison of the anomaloscope and three lantern types. Aviation, space, and environmental medicine, 76(5), 421-429.

SAE ARP4256, *Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft*

SAE ARP4067, *Design Objectives for CRT Displays for Part 23 Aircraft*

SAE ARP1874, *Design Objectives for CRT Displays for Part 25 (Transport) Aircraft*

SAE AS8034, *Minimum Performance Standards for Airborne Multipurpose Electronic Displays.*

Xing, Jing (2007). *Developing the Federal Aviation Administration's Requirements for Color Use in Air Traffic Control Displays.*

U.S. Department of Transportation
John A. Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142-1093

(617) 494-2000
www.volpe.dot.gov

DOT-VNTSC-14-13
DOT/FAA/TC-14/18