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Superseding ARP4032A

(R) Human Engineering Considerations in the Application of Color to Electronic Aircraft Displays

RATIONALE

The use color content as both a tool to increase situation awareness and as a sole information discriminator display has increased and will continue to increase. Correct implementation of these applications of displays is essential and critical to safe flight display applications.

SAE G-10 Aerospace Behavioral Engineering Technology Committee, specifically the G-10D Color Subcommittee, has been tasked to update this Aerospace Recommended Practice to provide current document color use guidance to implement increased use of color when used in and on flight decks and cockpits.

FOREWORD

While old generations of civil or military aircraft only had a limited number of colors, the newer glass cockpit generations started to use color in a far more extensive way than simply providing alerting information. The initial goal of ARP4032 was to issue recommendations on the use of colors for flight deck displays that, at the time, were mainly related to symbology color coding issues.

Currently the role of color in the fight deck/cockpit is expanding again far beyond coding symbolic information (alphanumerical, scale, graduations) or even larger areas, as display background or sky and ground in the primary flight display (PFD) or terrain and flight path data on navigation display (ND) including other multifunction displays such as electronic flight bags (EFB), EICAS and CDU data entry (see Acronyms List).

New features of modern cockpit are now including the need to displaying large color fields for a number of applications such as charting, terrain awareness and weather information products including own-ship weather radar, satellite weather data, etc. In turn, new considerations have to be taken into account as the use and the number of colors for coding large fields, cultural aspects of color and color "affordance" for representing information and environment with large fields; non coding use of color for large fields, color contrast for symbology overlaid on large field, etc. Additionally, attributes such as the level of transparency of the color used to code information in large fields needs to be considered. It is also necessary to review the integration of multiple color display features and intermixability, understood as resolution of the differences in the characteristics of the display hardware, or compatibility of displays from different manufacturers.

The goal of this document is not only to update the recommendations of the Initial ARP4032, but intends to address new considerations about the use of colors in modern flight deck design and practice.

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ACKNOWLEDGEMENT

The following document was a collaborative effort of many dedicated and experienced individuals who provided the perspective from a representative cross section of the international aerospace industry. Their efforts and contributions have resulted in a document that considers flight crew performance issues and implementation, certification and operational limitations and constraints. The following individuals and organizations have contributed directly to the development of this document.

We also wish to thank all the many individuals who contributed to the depth and quality of this document through their constructive reviews and comments.

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1. SCOPE

This document is intended for the application of color to cathode-ray-tube (CRT) displays, liquid crystal displays (LCD) and other types of display technologies such as projection displays. Emerging color display technologies other than those noted above, may not be adequately covered by these recommendations.

Color recommendations will not address Night Vision Devices (NVD), Head-Up Displays (HUD) or Head or Helmet Mounted Displays (HMD).

This document is applicable to aircraft as understood in 14 CFR Parts 23, Part 25, Part 27 and Part 29, and EASA CS-23, CS-25. CS-27 and CS-29 certification standards.

1.1 Purpose

This document makes recommendations concerning human factors issues in the application of color to flight deck display systems.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and 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.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP1782	Photometric and Colorimetric Measurement Procedures for Airborne Direct View CRT Displays
ARP1874	Design Objectives for CRT Displays for Part 25 (Transport) Aircraft
ARP4032	Human Engineering Considerations in the Application of Color to Electronic Aircraft Displays
ARP4033	Pilot-System Integration
ARP4102	Flight Deck Panels, Controls, and Displays
ARP4102/4	Flight Deck Alerting System (FAS)
ARP4102/7	Electronic Displays
ARP4102/7	Appendix A – Electronic Display Symbology for EADI/PFD
ARP4102/7	Appendix B – Electronic Display Symbology for EHSI/ND
ARP4102/7	Appendix C – Electronic Display Symbology for Engine Displays

ARP4153	Human Interface Criteria for Collision Avoidance Systems in Transport Aircraft
ARP4256	Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft
ARP4260	Photometric and Colorimetric Measurement Procedures for Airborne Electronic Flat Panel Displays
ARP5119	Location of and Display Symbology Requirements for Head-Down Electronic Flight Displays for Steep IMC Approaches
ARP5289	Electronic Aeronautical Symbols
ARP5364	Human Factor Considerations in the Design of Multifunction Display Systems for Civil Aircraft
AS8034B	Minimum Performance Standard for Airborne Multipurpose Electronic Displays

2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR 23	Airworthiness Standards: Normal, Utility, Acrobatic and Commuter Category Airplanes
14 CFR 25	Airworthiness Standards: Transport Category Airplanes
14 CFR 27	Airworthiness Standards: Normal Category Rotorcraft
14 CFR 29	Airworthiness Standards: Transport Category Rotorcraft
FAA AC-23.1309-1A	Equipment, Systems, and Installations in Part 23 Airplane
FAA AC-23.1311-1	Installation of Electronic Display Instrument Systems In Part 23 Airplanes
FAA AC 25-11A	Transport Category Airplane Electronic Display Systems
AC-25-11A	Electronic Flight Deck Displays, June 21, 2007
AC-25.773-1	Pilot Compartment View Design Considerations, January 8, 1993
AC-25.1309-1A	System Design and Analysis, June 21, 1988
AC-27-1B	Certification of Normal Category Rotorcraft
AC-29-2C	Certification of Transport Category Rotorcraft, FAA AC-29-2C

2.1.3 EASA Publications

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452 Koeln, Germany, Tel: +49-221-8999-000, www.easa.eu.int.

AMC 23	"Acceptable Means of Compliance," Certification Specifications for Normal Category Aeroplanes
AMC 25	"Acceptable Means of Compliance," Certification Specifications for Large [Turbine Powered] Aeroplanes
AMC 27	"Acceptable Means of Compliance," Certification Specifications for Small Rotorcraft

AMC 29 "Acceptable Means of Compliance," Certification Specifications for Large Rotorcraft

CS 23 Certification Specifications for Normal, Utility, Acrobatic and Commuter Category Aeroplanes

CS 25 Certification Specifications for Large [Turbine Powered] Aeroplanes

CS 27 Certification of Small Rotorcraft

CS-29 Certification of Large Rotorcraft

2.1.4 Other

Engineering Data Compendium, Human Perception and Performance, Edited by Kenneth R. Boff and Janet E. Lincoln, 1988.

CIE 2001 report, Commission Internationale de L'Eclairage (CIE), 2001, Improvement to Industrial Colour-Difference Evaluation, Technical Report CIE 142-2001, Vienna, Austria.

CIE 2001, Commission Internationale de L'Eclairage (CIE), 2001, International Recommendations for Colour Vision Requirements for Transport, Technical Report CIE 143-2001, Vienna, Austria.

CIE Publication No. 15.2 (1986), Colorimetry, 2nd Edition.

Farrell, R.J. and Booth J.M., 1984, Design Handbook for Imagery Interpretation Equipment, Boeing Aerospace Company, Seattle, Washington 98124.

Gannon, A., 2010, Flightdeck Aesthetics and Pilot Performance: New Uncharted Seas. In *Handbook of Aviation Human Factors 2nd Edition.*

Widdel, H. and Post, D., 1992, Color in Electronic Displays, Defense Research Series, Plenum Press, New York.

ISO/FDIS 9241-8.2, Ergonomic requirements for office work with visual display units (VDTs) – Part 8: Requirements for displayed colors.

NATO RTO TR-016 / HFM-012, Operational Color Vision in the Modern Aviation Environment 2001.

Stokes, Kite and Wickens, 1990, Display Technology Human Factors Concepts, SAE International, Warrendale, PA.

Wise, J.A., Hopkin, V.D., and Garland, D.J. (Eds.), 2010, *Handbook of Aviation Human Factors 2nd Edition,* Boca Raton, FL, CRC Press LLC.

2.2 Definition of Terms

Definitions used in this document shall be as noted in the Glossary of Terms defined in Appendix E.

The word "shall" is used to express an essential requirement where compliance is mandatory.

The word "should" is used to express a recommendation. Deviation from the specified recommendation shall require justification.

The word "must" is used to express an essential (mandatory) requirement that is required by a specific regulation.

2.3 Acronyms and Abbreviations

AC	Advisory Circular (FAA)
ADI	Attitude Director Indicator
AMC	Acceptable Means of Compliance (EASA)
ANP	Actual Navigation Performance
CDI	Course Deviation Indicator
CDU	Control Display Unit
CS	Certification Standards (EASA)
DEP	Design Eye Position
DERP	Recommend not using – Design Eye Reference Position
DGPS	Differential Global Positioning System
DMS	Digital Map System
EICAS	Engine Instrument Crew Alerting System
EFB	Electronic Flight Bag
EFIS	Electronic Flight Information System
ERP	Eye Reference Position
ESVS	Enhanced/Synthetic Vision System
EVS	Enhanced Vision System
FAR	Federal Aviation Regulations
FTE	Flight Technical Error
FOV	Field of View
FPV	Flight Path Vector
FPM	Flight Path Marker
HDD	Head Down Display
HMD	Head Mounted Display/Helmet Mounted Display
HUD	Head Up Display
JAR	Joint Airworthiness Regulations (JAA)
PFG	Perspective Flight Guidance

PFGD Perspective Flight Guidance Display

PFD Primary Flight Display

PF Pilot Flying

PNF Pilot Not Flying

QFPV Quickened Flight Path vector

SVS Synthetic Vision System

TCAS Traffic Alerting and Collision Avoidance System

3. ASSUMPTIONS

The assumptions about the system that guide and bound the recommendations contained in this document include:

3.1 Color will be used increasingly on all applicable displays and used for all phases of flight and lighting conditions throughout the day and night spectrum.

3.2 The pilot population does not exhibit uniformity of color vision. All types of color deficiencies are taken into account.

4. USES FOR COLOR

While most pilot certification standards include a requirement for some level of color vision in the applicant, color deficient users still need to be considered in the selection and use of color in aviation displays. First, there is no inherent need for color vision in the act of flying. Color requirements for all medical certification classes are based on the need to distinguish aviation light gun signals not a basic task need. The preamble to CAR 29, amendment 29-2[1], states that "a pilot who is unable to meet the color vision requirements in any way may be authorized to fly only with two-way radio communications available or under conditions where aviation lights would not be used for communication."

Because color, perhaps more than any other coding technique, enjoys such an undeserved reputation for ease of interpretation, the designer needs to understand the difference between absolute versus relative discrimination of colors and what it means to the application of color as a code.

Relative discrimination indicates that if two colors are placed next to reach other it is possible to tell that they are different. Absolute discrimination means that every time a particular color is presented the person observing it gives it exactly the same name or meaning, e.g., danger. The number of colors that are relatively discriminable is extremely high. The number of colors that are absolutely discriminable is in the order of eight to twelve colors.

The automotive industry has defined areas on the CIE Chromaticity chart where, for example, a certain proportion of observers call a color "red" These are elliptical contours on the chart showing 90%, 95%, etc. This research needs to be replicated for the flight crew population. The conclusion in RTO-TR-016 that all color specifications be stated in terms of the CIE coordinate system should be considered. It can be observed that the FARs do this for wingtip navigation lights, but for no other color use.

[1] "Color Vision, Near Vision, and Blood Pressure Requirements for Airmen," Civil Air Regulations Amendment 29-2 to CAR 29, "Physical Standards for Airmen; Medical Certificates," adopted February 13, 1951.

4.1 Attention-Getting and Alerting

4.1.1 Considerations

Color has been shown to be a practical means of alerting or drawing attention to specific information when applied within appropriate constraints (e.g., the color is in the observer's color sensitive field-of-view). Use of color alone as an alerting device is also affected by the associated background of similar color or contrast or separate displayed information of the same color and must be differentiated. A specific color maintains its attention-getting value only if it is used sparingly and consistently within cultural paradigms.

It may be difficult to discriminate between two similar-appearing colors such as yellow and amber. This is especially true when displayed on a multi-color displays under variant shifting ambient light conditions (see Farrell & Booth, 1984, and Boff & Lincoln, Engineering Data Compendium, 1988) and different viewing angles, e.g., cross cockpit.

The use of similar-appearing colors (proximate to each other in color space) either successively or simultaneously, on the same display may lead to a loss of attention-getting value as well as color confusions. These problems are more apt to occur when high ambient illumination falls on the display. This causes displayed color to become less saturated thereby reducing color differences. This effect of ambient illumination may become less serious for some color display technologies (e.g., LCDs) that may have a larger color gamut and be less susceptible to color shifts under ambient illumination. See the graphics of color confusion lines in Appendix C.

Forward field illumination levels need to be considered as they influence the perception of color. At the lower levels of forward field illumination the pilots will dim the displays to match. Crews will transition from daylight adapted, rods, color perception capabilities to dark adapted, cones, color perception capabilities. At the higher end of forward field illumination reflections off the display will de-saturate the colors. Also because of these reflections the luminance contrast of the displays is also decreased making the display less readable.

It should be noted that the attention-getting value of color is apt to be reduced for pilots with color vision deficiencies (see 3.4 and Section 9).

4.1.2 Recommendations

4.1.2.1 Small Field (such as symbology, alpha-numerics) traditional warning and cautionary colors (red and amber or yellow) should be reserved solely for this purpose, as the use of these colors for other functions will degrade their alerting value.

4.1.2.2 Large Field colors normally used for small field alerting (red and amber or yellow) may be used and should be addressed based on purpose. See Section 7.

4.1.2.3 A single display device should not employ colors that are closely spaced on a chromaticity diagram as these will appear similar and be difficult to discriminate (see Appendix C for example of a chromaticity diagram).

If closely spaced colors such as yellow and amber are employed, the ability to discriminate among the colors under all ambient conditions and viewing angles, as well as the maintenance of attention-getting value, should be demonstrated empirically.

4.1.2.4 For critical displays and alerting functions, color coding shall be redundant and supported by other visual or auditory information coding methods.

4.2 De-Cluttering

4.2.1 Considerations

Color can serve to group or organize information. This allows information to be transmitted more efficiently as long as the number of colors used for this purpose is limited. A large number of colors may actually be counter-productive to organizing information.

4.2.2 Recommendations

4.2.2.1 The number of colors used on a single display should be kept to a minimum for the purpose of intelligibility. See Section 5, Paragraph 5.1.1 for additional recommendations concerning the number of colors.

4.3 Coding

4.3.1 Considerations

4.3.1.1 Color-coding is a process by which different colors are used to represent different categories of information. For example, a red traffic signal means 'stop' while a green signal means 'proceed'. If color provides a completely unique source of information, the coding is called non-redundant. Color can also be combined with other coding dimensions such that two or more codes correlate with one another. This is referred to as redundant coding. (See Appendix A for further explanations of redundancy and partial redundancy.)

Cultural aspects of color have elicited some interest in early years of color displays introduction in non occidental cultures. This is not anymore an issue, as standardization of colors is now quite widespread. There is sometimes small colors variation among manufacturers, though color variations associated with symbolic representation do not represent a real issue. As a matter of fact, difficulties are now more on the consistency of symbol representation itself than on color coding.

4.3.1.2 Color has been shown to be effective as a coding scheme, particularly for qualitative information. Where more than a small number of coding categories exist, other coding schemes, such as alphanumeric, are more efficient for the transmission of the information. However, the use of color may still enhance information transmission if the separate categories can be logically divided into several major divisions. Each major division can then be coded via a different color. This is referred to as partial redundancy and has been shown to enhance search performance.

4.3.1.3 Redundancy permits people with color vision deficiencies to interpret color-coded displays. (See Appendix A for further description.) It may also reduce the impact of certain types of display failures such as individual electron gun failures in CRTs. Finally, in situations such as high ambient lighting conditions, redundancy can help to ensure the accurate transmission of information where colors alone may be difficult to distinguish even for persons with normal color vision.

4.3.1.4 Color codes should agree with commonly accepted practices, for example, red for warnings, yellow/amber for cautions and green for engaged or “O.K.” status.

4.3.2 Recommendations

4.3.2.1 In general, color should not be used to code quantitative information unless that information can be divided in to a small number of distinct categories such as has been done for color coded weather radar map displays.

4.3.2.2 Color-coding used for time critical information, shall be redundant with some other type of coding dimensions, such as shape or label.

Most avionics companies and airframers have established internal color standards that they have selected to use to both reduce errors (and thus training requirements) and to give their product a certain look and feel. In addition, a recent study has indicated that the better a cockpit and its displays look, the better the user feels the system performs (Gannon, 2010). Finally, most aviation licensing agencies (e.g., FAA, EASA) have also established a set of basic color coding standards.

4.3.2.3 The designer shall ensure that all relevant required standards are met and to verify that any conflicts are corrected to meet legal requirements (e.g., meeting the standard(s) or obtaining any required approvals for deviations), human factors standards, and the company’s own standards.

This document does not provide any specific standard but rather the general perceptual and human factors guidelines that should be used as the principal criteria to help make the appropriate trade-offs when such decisions between conflicting requirements need to be made.

4.4 Contrast and Legibility

4.4.1 Considerations

4.4.1.1 The judicious application of color can serve to enhance the contrast between items or areas, as compared to luminance contrast alone. Although luminance contrast has been shown to be the most important factor in the legibility of alphanumeric and graphic symbols, the proper application of color can enhance legibility. This can be accomplished through the use of symbol and background colors that are widely spaced on the CIE chromaticity diagram. The use of opponent colors, such as red-green and blue-yellow, for example, will yield wide spacing. If luminance contrast is already sufficient for adequate legibility, the addition of chromatic contrast may not yield any significant improvement in legibility.

4.4.1.2 Blue has been shown to have poor legibility characteristics that stem from three major factors:

1. In CRT displays, the blue phosphor has a low luminance output compared to other primary phosphors;
2. Blue tends to be focused in front of the retina; and
3. There is a relative scarcity of blue receptors in the fovea of the eye, as compared to those for red and green.

Consequently, the poor legibility characteristics of blue are due to limitations of both current display technology and the human visual system.

Another impact of color on legibility is the potential consequences of color illumination, for example, colored cockpit lights or color emissions from a self luminating display (e.g., CRT, LCD) can have on the perception of surface colors (e.g., painted labels) illuminated by light from those displays.

Color stereopsis is the apparent difference in depth between two objects of different color lying in the same plane. Color stereopsis, or chromostereopsis, may result from differential dispersion of colored light due to chromatic aberration of the eye. The apparent depth separation between differently colored visual stimuli varies as a function of the decentration distance of light as it enters the pupil. It also varies as a function of the optical power of prisms placed in front of the eyes. The direction of decentration, or whether the prisms are converging or diverging, determines which color will be seen in front of the other (see Engineering Data Compendium, 1988).

4.4.1.3 Contrast Polarity and Background/Foreground Color Contrast

Classically (ISO FDIS 9241-8 Requirements for displayed colors) contrast polarity is defined as positive polarity being black on white while negative polarity is white on a black background. Following Walraven (RTO TR-016 / HFM-012), the advantages and disadvantages of negative polarity for aeronautical displays are, respectively, power consumption and flicker reduction on one side, and increased specular reflections and compatibility with outside the cockpit brightness on the other.

Beyond these considerations, early studies on color contrast on CRTs have shown that adequate legibility could be achieved in both cases (positive dark on light and negative light on dark) provided the adequate background and foreground color were selected. As an example, orange information on a dark green background is known to produce very good results in term of visibility while light green on a white background is usually quite bad.

Maintaining an adequate color contrast becomes a difficult issue with introduction of weather radar or terrain awareness displays with overlaid alphanumeric or symbolic information, especially if colors that are close to one another in color space must be used for the background and foreground information. It may be necessary to find a way to restore an adequate color contrast when background and foreground information using same or similar color(s) happen to be superimposed.

4.4.1.4 Night Operations Considerations and Dark Adaptation

There are requirements to dim display brightness and cockpit illumination for night operations and night adaptation-accommodation.

Electronic displays are required to be dimmable to low levels of luminance in order to allow for some degree of dark adaptation by the pilots to facilitate out the window viewing at night. The actual dimming requirements are given in AS8034B and ARP4256A that state: “For low ambient conditions, the display should be dimmable to levels that allow for the flight crew’s adaptation to the dark, permitting visibility of out of the window. In dark conditions, the minimum white symbol luminance when measured in a dark ambient shall be no greater than 0.343 cd/m^2 (0.1 fL) for 0.6 milliradians wide lines. In addition, a luminance of 0.171 cd/m^2 (0.05 fL) will be desired by a small percentage of users.”

These luminance and illumination conditions result in the visual system operating in the mesopic range of vision (approximately 0.003 to 3 cd m^{-2})* which is intermediate between the photopic and scotopic ranges of vision. In the photopic visual range, full color vision is possible as the cones are operating effectively. In the scotopic visual range there is virtually no color discrimination available since it is governed by the rods. In the mesopic range of vision, there is a loss of color discrimination similar to that of the color deficiency known as tritanopia where there is a loss of discrimination along the blue-yellow color axis. This means that discrimination between blue and green, between yellow and white as well as between red and magenta becomes more difficult. Hence, these low levels of display brightness drive color separation requirements for displays, especially along the blue-yellow axis.

*NOTE: There is considerable variation in the literature as to the actual mesopic range. It is defined variously as between 0.034 and 3.4 cd/m^2, between 0.01 and 3 cd/m^2, and between 0.001 and 3 cd/m^2. In every case however, the minimum display luminance required for dark ambient conditions falls well within the mesopic viewing range.

4.4.2 Recommendations

4.4.2.1 Designers using color should find a way to maintain or restore an adequate color contrast, e.g., using a neutral background underlay behind alerting text (gray), when background and foreground information using same or similar colors are superimposed.

4.4.2.2 Highly saturated blue colors with short dominant wavelengths, for example, blue phosphor of CRT by itself, should not be used for alphanumeric or symbol containing fine spatial detail. Adequate legibility shall be demonstrated if any blue is used where fine spatial detail is important.

4.4.2.3 When designing day/night imaging/display systems requiring color discriminations, the designers shall consider human physiology issues on color perception.

5. NUMBER OF COLORS

5.1 Considerations

5.1.1 Numbers of Colors for Coding

The use of more than seven colors for coding applications in small fields, may degrade performance on search, identification and coding tasks (organization) particularly where memory recall is important. This is due both to poorer discriminability (especially under high ambient light) and a loss of organizational value. With display technologies such as LCDs, the loss of discrimination due to high ambient illumination may become less significant. Even though colors may maintain their chromaticity specifications under higher ambient illumination, the use of more colors will still adversely affect organizational value.

5.1.2 Color Usage in Scene Imagery

Scene imagery can be used to give the pilot a electronically enhanced or synthetic image representation of out of the aircraft scene in low visibility conditions as it offers a clear improvement in pilot spatial awareness, terrain awareness, etc.

Multiple colors and shades of color are needed to represent a realistic image. The number of colors used should not be constrained, but the saturation and luminance of colors shall not detract from the readability of critical overlaying symbol or alpha numeric information.

The use of saturated colors, i.e., colors near full grayscale intensity, should be avoided since the brighter colors should be used for overlaying symbol or alpha numeric information on the scene.

Other graphics techniques should also be employed to maximize the readability of symbols and alpha numeric data. Providing a dark halo (or stroke outline) around symbols and alphanumeric data increases the ability of the pilot to detect and recognize the characters and symbols. Using color contrast can also assist in critical information being detected on a busy background image.

5.2 Recommendations

5.2.1 Color should be applied in a conservative manner, that is, the smallest number of colors that can be shown to enhance the detection and transmission of information shall be used.

5.2.2 No more than seven colors shall be used for coding to differentiate high information content displays. These include white, red, green, yellow (or amber), magenta (or purple), and cyan (or aqua).

5.2.3 The selection of a large scale color can impact the control of ambient lighting – for example at night, helping to keep the total energy stimulating the retina to a minimum one would want to use a color to which the eye is not very sensitive, e.g., dark blue.

The selection of a large field colors must account for the ability to attain the desired contrast between the background and the data being presented.

In this regard, in certain situations (e.g., an off normal situation) large field color could be valuable to use colored background to provide, for example, higher contrast for important data and lower contrast for less important data.

Large scale color can be used to mimic “reality” – blue for sky and brown for ground.

Large scale color could be used for enhancing performance. For example, if components of system B use a background color light blue and if system Y uses a background color of yellow, then a system that has interactions with both system B and system Y, could be indicated by a background color of green.

5.2.4 The use of more than these colors are not precluded. However, careful testing should be undertaken to ensure that the use of a larger number of colors improves task performance. See Section 10 for testing considerations.

5.3 Color Specification

5.3.1 Considerations

5.3.1.1 No single color difference measure that is currently available will give an accurate measure for all tasks involving the use of color. New metrics, as those reported in the CIE 2001 report (Commission Internationale de L’Eclairage (CIE), 2001, Improvement to Industrial Colour-Difference Evaluation. Technical Report CIE 142-2001) may be a better predictor of color discrimination performance.

5.3.1.2 For tasks involving color discrimination, CIELUV delta E* could be replaced by CIE delta E*00. Unfortunately, some problems still exist with this measure that precludes its use as a completely precise measure. Hence, it is difficult to specify a satisfactory minimum acceptable color difference at this time. However, CIE delta E*00 can be used to maximize the perceptual differences among colors.

5.3.1.3 For tasks involving symbol legibility, CIE delta E*00 could not be the adequate metrics and several other methods have been used in an attempt to predict legibility performance.

5.3.1.4 No single color difference measure has been shown to be more than a poor to fair predictor of performance on tasks involving color identification where colors presented in isolation must be absolutely identified. This requires the use of a small set of colors that are widely spaced perceptually. Color difference measures such as the latest CIE delta E*00 should be used as a preliminary selection guide for this purpose.

5.3.2 Recommendations

5.3.2.1 In all cases where performance is tied to color discrimination, final color specification must be based on actual tests of the equipment in actual or simulated use conditions. The application of color should improve performance and hence color should not be added just for aesthetic value. Where a decrement in performance is demonstrated, the use of color should be avoided.

5.3.2.2 For color difference measures preliminary selection, it is recommended that the latest CIE delta E*00 be used.

6. EFFECT OF FEATURE SIZE

6.1 Considerations

6.1.1 As feature size is reduced below 30 arc minutes of visual angle, blue and yellow colors become increasingly difficult to distinguish from one another. This is also true for red and green colors but not until the subtended visual angle decreases to about 15 arc minutes.

6.1.2 Correction factors should be used in the color difference equations in order to compensate for the small-field effect in the various color difference metrics (see Appendix A). These correction factors are valuable for re-scaling color differences among colored stimuli that subtend small visual angles such as alphanumeric.

6.2 Recommendations

As feature size is reduced, the designer shall ensure that perceived color differences are maintained.

7. APPLICATION OF COLOR TO LARGE FIELDS

7.1 Considerations

The primary concern is the use of color in depiction of topography, terrain alerting, and weather.

7.1.1 Bordering and Transparency

When applying color to large graphical fields that overlap each other (e.g., weather radar over topography), the colors may obscure one another or other relevant symbology and text. A common approach to ensure proper visibility of these objects is to utilize transparency (alpha values) to allow background objects to be visible beneath the large fields.

Bordering (outlining) may be used to disambiguate and accentuate edges of large fields of color in combination with transparency.

7.1.2 Affordance: Significance of Colors on Large Field

True Affordances[2], are innate, directly perceived, without necessity of an intermediate representation.

The idea of affordance[3] is that the intent of used colors should be as intuitive as possible, based prior basic acquired knowledge and experience. Using RED flame symbology on a large field, in an associative relative position, to indicate an engine fire, is an example of affordance for a pilot.

A false affordance is an apparent affordance that does not have any real function, meaning that the actor perceives nonexistent possibilities for action. When affordances are perceptible they *offer a direct link between perception and action*, and when affordances are hidden or false, they lead to mistakes and misunderstandings.

7.1.3 Identical or Similarly Coded Information and Background

When using similar colors on a large field, e.g., a yellow caution alert on a field depicting a built-up area, normally shown in yellow or amber as well, it is necessary to deconflict the similarly colored data. One possibility is to make local priorities change on one of the elements displayed, to emphasize one over the other, possibly by elevating or raising the alert to appear above the background field or haloing it.

With the use of similar local colors, the designer shall provide a means of differentiation.

7.2 Recommendations

7.2.1 Do not use colors that are close in color space for high priority information, e.g., crew alerting, on similarly colored large field backgrounds.

7.2.2 To mitigate the potential effects of unwanted alpha blending between background and foreground colors, appropriate levels of transparency should be used to reduce the probability of an unintended color. Dissimilar colors should be used to discriminate between large fields having similar importance but dissimilar meaning.

7.2.3 Criticality of any symbols that are overlapped shall be evaluated, and those critical (e.g., an EGPWS or WARNING alert) shall be placed on top of the semi-transparent large field.

7.2.4 Border colors shall be coordinated with the large field fill color to ensure that the object is perceived as a single element, not two elements (line and fill). Additionally, borders shall utilize colors that are distinct from other line elements in the display to avoid confusion.

7.2.5 Irrelevant information (layers) shall be removed to avoid unnecessary or potentially misleading formation.

7.2.6 When using colors on a large display field, the meaning of the color should be intuitive, requiring little or no cognitive processing, and provide a direct link to intended meaning or function.

7.2.7 With the use of similar local (e.g., close in color space) colors for different functions, the designer shall provide a means of differentiation.

8. CHARACTERISTICS OF THE USER POPULATION

8.1 Considerations

8.1.1 The global population of dyschromatic subjects is considered to be around 8% of the male population with an extremely small number of cases (0.5%) in the female population.

[2] See Affordance, James Gibson, “The Ecological Approach to Visual Perception”, pp. 127-143, 1979
[3] See Affordance, Donald Norman, “The Design of Everyday Things”, pp. 87-104, 1988

8.1.2 Although pilots with Class I physicals are required to have normal color vision, this should not be interpreted to mean that all of these pilots have perfect color vision.

8.1.3 Approximately 1% of U.S. Class I pilots have obtained medical waivers for color vision.

According to a summary calculated by the Aerospace Medical Certification Division (AAM-300) of CAMI, as of October 12, 2010, the FAA currently has a total of 3303 pilots waivered for color vision based on passing the signal light gun test and distributed as follows:

- 1296 Class 1 (1.2%)
- 755 Class 2 (0.8%)
- 1252 Class 3 (0.35%)

This represents a small percentage of pilots.

8.1.4 Some of the tests employed to certify pilots as having normal color vision are designed to pass individuals with mild to moderate color deficiencies, particularly of the red-green type. Consequently, there is considerable variability in color vision performance among pilots that have been classified as having normal color vision.

The severity of pilot color deficiencies is unknown. U.S. pilots failing their initial screening test may request secondary screening involving identifying red, green, and white lights projected from a Signal Light Gun. If they pass that test, they are given an occupational color vision test. EASA established different alternative color testing requirements, and applicants who fail further color perception testing shall be assessed as unfit.

8.1.5 Beyond congenital color defects, some acquired color defects are also possible. For example, results of specific medication, or it is common for the lens of the eye and the macula to become yellowish with age. This means that the eye becomes less sensitive to colors containing blue and color discrimination for those colors is reduced. In addition, the range of accommodation becomes restricted with age, which may hinder the focusing of extreme wavelengths such as red and blue.

8.1.6 Effects of Hypoxia on the Perception of Color (Contrast)

Alterations in color discrimination increase slightly but significantly as barometric altitude increases. Impairments occur mainly in the red and blue ranges. In addition, results further indicate that color discrimination is affected only when a minimum threshold of difference between color stimuli is not present.

As a consequence of these above characteristics, maximum color spacing should be employed.

NOTE: Hypoxia is not an normally issue when flying/operating at a normal cabin pressure (≤8000 feet barometric altitude).

8.2 Recommendations

Redundancy should be used to help offset the problems encountered by individuals with color vision deficiencies.

9. COLOR IMPLEMENTATION EVALUATION

9.1 Considerations

9.1.1 At the present time there is no analytical model available that will consistently predict the effects of chromaticity, display luminance, ambient luminance, symbol size, symbol shape, or color vision deficiencies on performance with a color display. This currently means that the only way to determine the effectiveness of a display is to actually test it with observers in tasks and conditions equivalent to the operational environment.

9.2 Recommendations

9.2.1 The display designer should document how the following issues have been addressed.

9.2.1.1 If color was used for attention getting or alerting functions, or both, how was its effectiveness ensured?

9.2.1.2 Does the assignment of particular color codes adhere to commonly accepted practices?

9.2.1.3 How has the redundancy of color-coding implemented? Color coding and implementation should be the redundant method of displaying the data or symbology.

9.2.1.4 How have the chromaticity and luminance relationships tracking been documented over the luminance range?

9.2.1.5 Are manual and automatic brightness and contrast controls employed and are they effective?

9.2.1.6 How have the number of colors and the choice of colors for a given format4 been evaluated?

9.2.1.7 How was each color assessed for adequate contrast under all likely background and ambient illumination conditions?

9.2.1.8 How was it ensured that under expected lighting conditions (twilight, dark and high ambient brightness including direct sunlight) color degradation would not adversely affect interpretation of the display?

9.2.1.9 How were the color vision characteristics of the intended user population considered?

10. INTEGRATION OF MULTIPLE COLOR DISPLAYS ON THE FLIGHT DECK.

10.1 Considerations

10.1.1 Integration of multiple color displays on the flight deck raises a series of issues: Beyond aesthetic considerations, uniformity of colors, particularly as related to aging of the displays (physical color degradation), and/or consistency of meaning/application on different displays, used though out the flight deck needs to be addressed carefully as related to crew/user performance.

10.1.2 AS8034B describes the allowable shift of color in one specific display. However, the use of multiple displays on the flight deck requires us to also specify the viewing envelope and, for multiple displays, to consider the uniformity of color for a given set of displays and installations. This includes the cross check of information between crew members stations as well as the variability of displays provided by different manufacturers and/or technologies are also a source of concern.

10.1.3 Individual Display

For a given individual display position within the cockpit, SAE document AS8034B defines color uniformity at any position within the useful display area as well as over the viewing envelope.

To define the display envelope the display installation versus pilot and copilot DEP should be considered (see AS8034B § 11.4 regarding specific cross-cockpit consideration).

In the case of one unique installation the viewing envelope depends on the DEP[5] and all eye positions (ARP4102).

[4] See FAA AC25-11_ for format definition
[5] See FAA AC 25.773-1 Pilot Compartment View Design Consideration

10.1.4 In most flight decks, the same type of display is installed at several locations. While AS8034B, ARP4256A, and ARP1874 address a single installation, one needs to consider the total viewing envelope of all installation positions in reference to the design eye reference point. Two types of viewing envelopes need to be considered: a primary field of view which entails those displays that are primarily used by each flight crew member separately and an extended field of view in which one flight crew member is required to view the other flight member's displays (cross-check capability).

10.1.5 Intermixing displays from multiple suppliers and/or intermixing display technologies requires that one consider both the overall consistency effect as well as the possibility that misleading information could result.

10.2 Recommendations

10.2.1 Removed.

10.2.2 The extended field of view involves the cross check of information presented on the other flight crew members displays. AS8034B requires that the viewing envelope of a display be defined by the display manufacturer. However, as stated by ARP4256A, the requirement for cross cockpit viewing angles may far exceed the specification of the individual display envelope.

Taking that into account, minor changes in chromaticity can be tolerated as long as colored information is not misleading. Any change in chromaticity shall not interfere with the intended function (as an example: color as an aid for symbol separation or color to convey the meaning of similar shaped objects). Compliance with these rules should have to be checked under simulation and flight testing.

10.2.3 It shall be shown that when installed on a flight deck or in a cockpit, intermixing displays from different manufacturers will not pose safety of flight problems and that the displays are compliant with AS8034B.

10.2.4 Adjustment of colors ranges should be allowed for fine tuning of color uniformity throughout the different displays. Color shifts between different displays should be permitted with respect to safety of flight as long as associated color information is not misleading

10.2.5 Since the color gamut[6] between multiple display sources and especially between different display technologies may vary significantly, a display system designer shall ensure that the intended function of the color coding is maintained.

11. NOTES

11.1 A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY SAE SUBCOMMITTEE G-10D COLOR DISPLAY OF
COMMITTEE G-10, AEROSPACE BEHAVIORAL ENGINEERING TECHNOLOGY (ABET)

[6] "**color gamut**" (/ˈɡæmət/), is a certain *complete subset* of colors. The most common usage refers to the subset of colors which can be accurately represented in a given circumstance, such as within a given color space or by a certain output device, Wikipedia, http://en.wikipedia.org/wiki/Color_gamut, 2013.

APPENDIX A - FORMULAE

CIELUV delta E*:

luminance within the image under consideration. u ' n and v 'n = values of the reference white under consideration. Normally, these are coordinates for CIE standard illuminant D65 (u ' n = 0.1978 and v ' n = 0.4684)

u' = 4X / (X + 15Y + 3Z) or
4X / 2 + (167 v ') 2]1/2

where:

YM = the luminance of the brighter of a character/background pair

It is to be noted that the constants in the equation were derived such that 100 E units of contrast are predicted to yield asymptotic reading speed performance.

LUMINANCE CONTRAST:

Contrast: Maximum luminance demonstrating the concepts of purity and dominant wavelength.

APPENDIX B

Background Data and Research on Color Vision

While most pilot certification standards include a requirement for some level of color vision in the applicant, there are several reasons why color deficient users need to be considered in the selection and use of color in aviation displays. First, there is no inherent need for color vision in the act of flying! Color requirements for all medical certification classes are based on design practices, not a basic task need. For example, the FAA regulations state that all pilots must have “the ability to perceive those colors required for safe performance of airman duties.” They note that “color vision is essential for recognizing aircraft position lights, light-gun signals, airport beacons, approach slope indicators, and chart symbols, especially at night.” (14 CFR Part 67 revised 9/16/96) There is nothing in the above criteria that has anything to do with the ability to safely fly the aircraft! Rather it only addresses the ability to deal with the accidental design requirements imposed on the aviation system by technologies and regulations created long before the Americans with Disabilities Act. As a result, given that airline pilots can make very large salaries, it is reasonable to expect that someday there could be a class action suit against civil aviation agencies to eliminate this requirement as being unnecessary and discriminatory. But in the short term, it is even more important to remember that even under the current regulatory environment, applicants can pass the approved color vision test without having “perfect” color vision. Thus, there are certified pilots who may have difficulty visually discriminating between different colors codes.

There is no empirical evidence to indicate that color is a more efficient or effective coding technique for alerting or informing users than other well designed coding approaches.

Color coding has inherent limitations. Very few avionics interface designers have studied human color perception. Improper use of color can distract the flight crew. Improper use of color can *artificially* group items because they are all close to the same color. Color can actually become noise and slow down or cause the user to make mistakes, e.g., the Stroop Effect. The sole use of color as a code discriminates against those with non-perfect color vision (possible violation of the Americans with Disabilities Act). As a matter of fact approximately 12% of all males and about 1% of females have some form of color deficiency – designers need to remember pilots are only tested on their ability to perceive certain colors not all of them.

Basic Limitations of Human Color Vision

Humans can only perceive color in the center of their visual field.

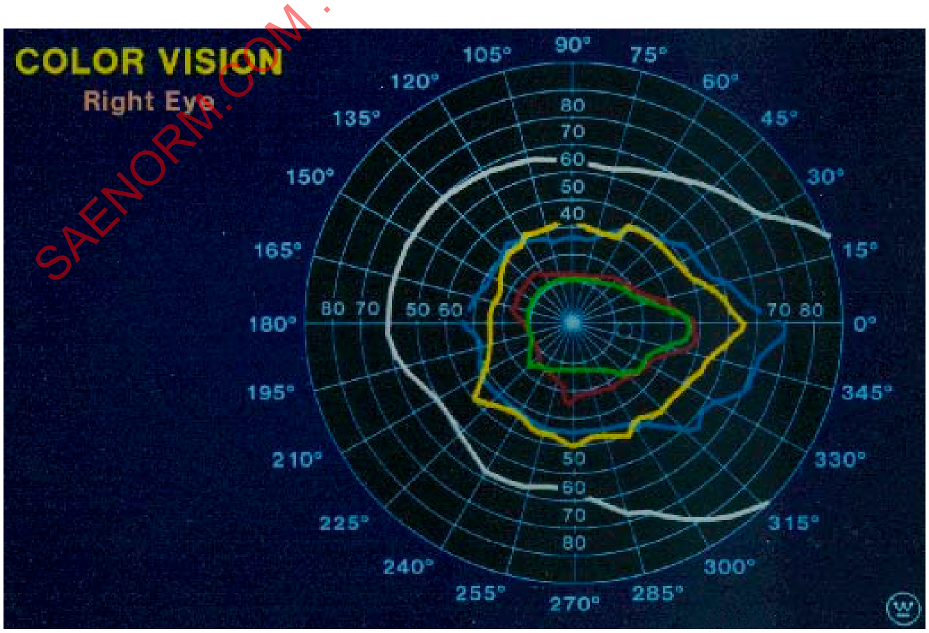

FIGURE XX - MAP OF COLOR SENSITIVE AREAS IN A HUMAN’S RIGHT EYE

The white line indicates the limits of vision because to the physical features of the face (e.g., eye brow, nose, cheek). The yellow, blue, red, and green lines indicate the area on the retina where that color can be seen. As can be seen, color can only be perceived in the center of the visual field. In the periphery only shares of gray can be distinguished. Thus, the designer should not expect color coding to be effective in those areas of the cockpit unless the pilot looks directly at the location.[7]

The more colors codes used the higher the probability that the user will make errors in assigning the intended meaning to them. For an example see the following table.[8]

TABLE YY - ABSOLUTE DISCRIMINATION ERRORS VERSUS NUMBER OF PROPERLY SELECTED COLORS

Number of Colors	Percent Errors
10	2
12	4
15	5
17	28

Human Perceptual Dimensions and Coding

Perceptually color has three dimensions: hue, saturation, and brightness. Hue is associated with the wave length of the light and is normally associated with the dimension of color to which we give names, e.g., red, green, blue. Saturation is the perceptual consequence of mixing white light with a single wave length. It can be thought of as starting out with a pint of pure red paint (highly saturated) and then slowly mixing more and more white paint until one can just perceive a hint of red very low saturation. Brightness is associated with the amount of perceived energy being received. Brightness is so perceived both with the amount of energy emitted and because the sensitivity of the eye (like any sensor) varies with the attributes of the stimulus and the sensor. If a sensor is more sensitive to high frequencies than lower frequencies then the same amount of high and low frequencies will be perceived as having more high frequency input than low frequency input. The human eye like most sensors is more sensitive to the middle of the visible spectrum than to the parts of the spectrum closer to it limits.

Perceived large amount of energy being very thought of as bright, and minimal amount of perceived energy being very dim (i.e., approaching black). Assume the same amount of energy emitted, those wavelengths in the middle of the perceived spectrum are perceived as being brighter than those near the limits.

Perceptually the Munsell color space is continuous along all three dimensions even though most depictions (such as Figure M depict them as discrete) and only show two dimensions.

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7 Wise, J.A., M.C. Culver, & N.C. Abi-Samra. (1987). *Display Design for Dispatch Control Centers in Electric Utilities: Handbook.* Electric Power Research Institute Report No. EL- 4960. Palo Alto, CA: Electric Power Research Institute.

8 Ibid

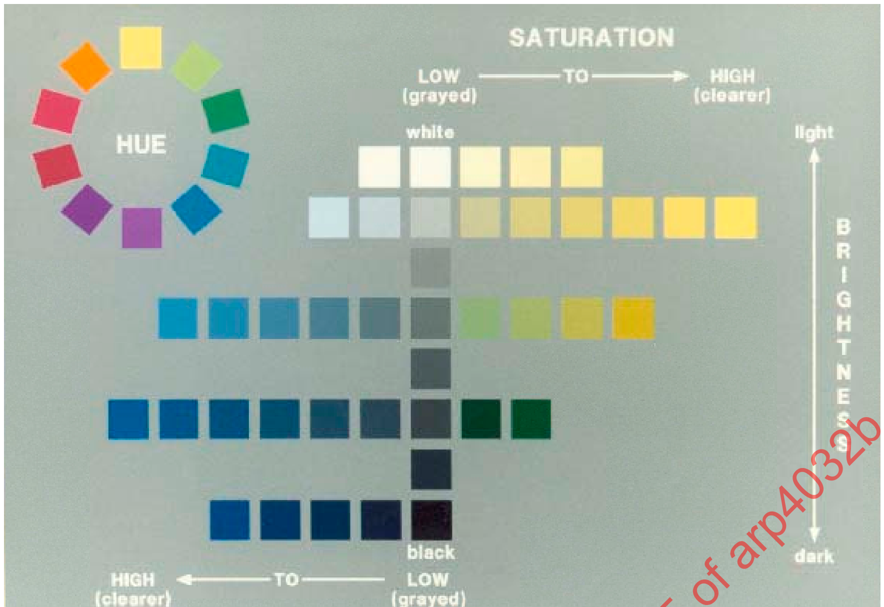


FIGURE M = A SLICE THROUGH THE MUNSELL COLOR SPACE

Cognitive Attributes of the Color Stimulus

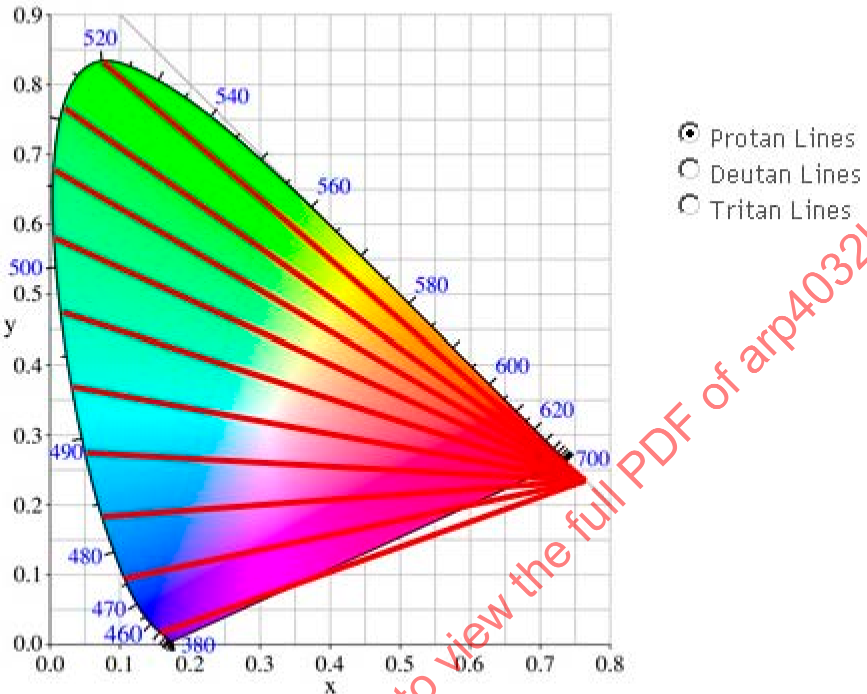
The cognitive treatment of the three perceptual dimensions is rather different. Brightness and saturation are treated as continuous dimensions, but hue is treated as a set of discrete stimuli. The simplest way to remember this distinction is the way human describe each o these dimensions. Humans describe the saturation[9] dimension as being more or less saturated. Likewise, the brightness[10] of a color is described as being more or less bright. Hue on the other hand is generally treated as a set of discrete entities. The most basic and powerful proof of that is that humans have given names to the cognitive consequences associated with different hues, e.g., red, green, blue, yellow.

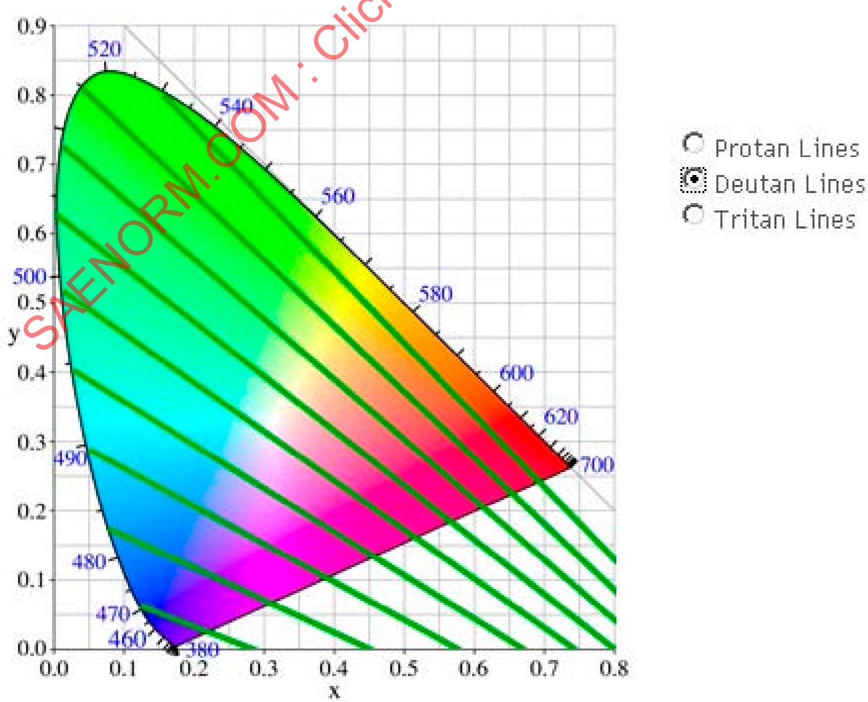
Because humans naturally treat the three dimensions of color differently, the use of the color in terms of coding should follow that natural cognitive process. That is, hue should be used to code different kinds of things, e.g., airplanes, cars, mountains. Brightness and saturation on the other hand will be more effective as coding some continuous dimension associated with some entity. For example, different types of aircraft (e.g., air freight, passenger, corporate jets, ultra-lights) could be coded using different hues. The weights of the type of aircraft type that are coded using red, could indicated using saturation. For example, a completely saturated red could represent an aircraft of that type that is at max gross weight, while very low saturated red could represent an aircraft of that type a minimum weight. The aircraft weights in between would be coded based on the percent of the available weight, e.g., an aircraft at half weight would be at the perceptual mid point of the available saturation range.

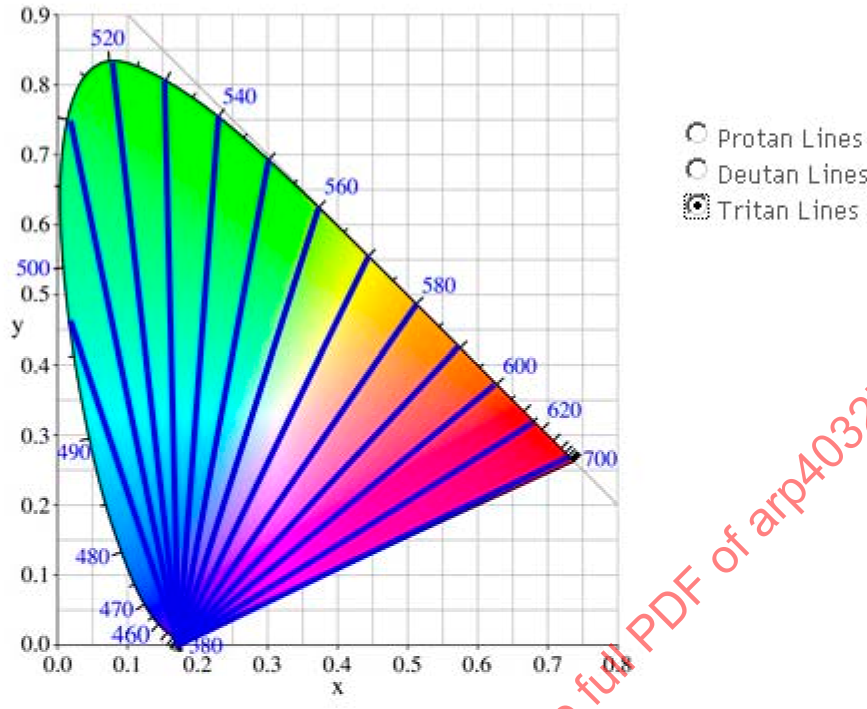
The point to remember is that what makes a variable continuous or discrete is not the physical nature of the variable, but rather how humans process the perceptual information about the variable. If as above, the user is interested in the relative values then a continuous coding technique may be best. If however, the user is only interested in does the aircraft have or not have the fuel needed to complete the assigned mission then a discrete color coding technique could be used.

[9] This is not to infer that professionals do not or cannot exactly measure the degree of saturation, but rather how it is normally treated by ordinary observers, rather than scientists and engineers. It should also be noted that scientists and engineers outside of a profession setting will normally describe saturation as continuous, e.g., more or less saturated.
[10] This is not to infer that professionals do not or cannot exactly measure the degree of brightness, but rather how it is normally treated by ordinary observers, rather than scientists and engineers. It should also be note that scientists and engineers outside of a profession setting will normally describe brightness as continuous, e.g., more or less bright.

On the other hand, the display user was only interested in distinguishing those aircraft carrying hazardous cargo from those that are not carrying hazardous cargo the most appropriate color coding attribute would be hue. And if one wanted to distinguish between those carrying a lot of hazardous cargo from those carrying very little the most appropriate color code may be the saturation, where highly saturated would indicate more hazards and low saturations indicate low levels.






0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
y
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x
520
540
560
580
600
620
700
500
490
480
470
460
380
Protan Lines
Deutan Lines
Tritan Lines

APPENDIX C - AREAS IN NEED OF FURTHER DATA AND RESEARCH

If adequate predictive models are to be developed for application in the future, some specific questions and issues must be addressed, and designers should be aware of these shortfalls, and may be able to provide answers in their design and implementation process. The following is a partial list of examples of issues where data are currently lacking. This list should in no way be considered exhaustive but merely serves as an example of the types of issues that must be addressed.

1. What coding dimensions (for example, chromaticity, symbol shape, luminance, etc) are optimal for specific functions (for example, alerting, decluttering, etc.)?

2. How do these coding dimensions interact, how many can or should be used together, and what are the most effective combinations in making redundant codes?

3. How many codes or coding dimensions, or both, may be introduced before performance begins to degrade?

4. How does varying the number or separation of colors, or both, in color space affect their efficiency in alerting functions? Can the efficiency be changed through the use of redundancy?

5. How can the legibility of symbols be modeled to show the effects of: symbol size, symbol shape, chromaticity, symbol luminance, ambient luminance, contrast, in combination, or separately?

6. How does performance on color vision tests and classification systems relate to performance of dedicated tasks using color displays?

7. How well do currently available measures of perceived color differences and legibility (for example, CIELUV, CIELAB, FMC, etc.) perform relative to one another? Under what conditions? How well and under what conditions do these tests predict performance on dedicated tasks?

8. How do chromatic contrast and luminance contrast combine to affect recovery from display/forward field of view adaptation mismatches?