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

RATIONALE

This document has been reaffirmed to comply with the SAE 5-year Review policy.

FOREWORD

This revision contains format/editorial changes only.

ACKNOWLEDGEMENTS

The SAE G-10 Committee would like to extend special recognition to the following individuals for the dedication and hard work they put into preparing this document:

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1. SCOPE:

Although this document is specifically intended for the application of color to cathode-ray-tube (CRT) instrumentation, most portions are also compatible with other emerging electronic display technologies, whether they are self-luminous or light modulating devices, such as liquid crystal displays. However, it is not intended to address the concerns brought about by the use of specialized equipment such as head-up displays and night vision goggles. Identifiable incompatibilities or special considerations for color display technologies other than the CRT have been noted in the recommendations.

1.1 Purpose:

This document makes recommendations concerning human factors issues in the application of color to self-luminous display instrument systems.

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2. 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 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP1782 Photmetric and Colormetric Measurement Procedure for Direct View CRT Display Systems (under development)
ARP1874 Design Objectives for CRT Displays for Part 25 (Transport) Aircraft (under development)
ARP4102 Flight Deck Panels, Controls, and Displays (under development)
ARP4102/7 Electronic Displays (under development)
ARP8034 Minimum Performance Standard for Airborne Multipurpose Electronic Displays

2.2 FAR Publications:

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591.

FAR Part 25

2.3 Other Publications:

FAA Advisory Circular No. 25-11. Transport Category Airplane Electronic Display Systems
CIE Publication No. 15.2 (1986) - Colorimetry, 2nd Edition

3. USES FOR COLOR:

3.1 The use of color on visual displays has been shown to be effective in improving performance on search and identify tasks in which the identification or location, or both, of specific qualitative information is important. For example, color has been shown to be more effective than shape, size, or alphanumerics when certain types of information need to be located quickly within a display.

3.2 Attention-Getting and Alerting:

3.2.1 Considerations:

3.2.1.1 Color has been shown to be a practical means of drawing attention to specific information when applied within appropriate constraints.

3.2.1.2 A specific color maintains its attention-getting value only if it is used sparingly and consistently.

3.2.1.3 It may be difficult to discriminate between any two similar-appearing colors such as yellow and amber. This is especially true when displayed on a multi-color CRT under high ambient illumination conditions.

3.2.1.4 The use of similar-appearing colors, 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 colors to become less saturated, thereby reducing color differences. This effect of ambient illumination may become less serious for some emerging color display technologies that may have a larger color gamut and be less susceptible to color shifts under ambient illumination.

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

3.2.2 Recommendations:

3.2.2.1 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.

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

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

3.2.2.4 For critical alerting functions, color should be redundant with other visual or auditory information coding methods.

3.3 De-Cluttering:

3.3.1 Considerations:

3.3.1.1 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.

3.3.2 Recommendations:

3.3.2.1 The number of colors used on a single display should be kept to a minimum for the purpose of de-cluttering. See Section 4 for additional recommendations concerning the number of colors.

3.4 Coding:

3.4.1 Considerations:

3.4.1.1 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.)

3.4.1.2 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 alphanumerics, 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.

3.4.1.3 Redundancy permits people with color vision deficiencies to interpret color coded displays. It may also reduce the impact of individual electron gun failures in the CRT itself. 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.

3.4.2 Recommendations:

3.4.2.1 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.

3.4.2.2 Color coding that is redundant with some other coding feature should be used for the reasons listed above.

3.4.2.3 Color codes should agree with commonly accepted practices, for example, red for warnings, yellow for cautions, and green for engaged or 0.K. status.

3.5 Contrast and Legibility:

3.5.1 Considerations:

3.5.1.1 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.

3.5.1.2 Blue has been shown to have poor legibility characteristics that stem from three major factors: (1) The blue phosphor has a low luminance output compared to other primary phosphors; (2) Blue images tend to be focused in front of the retina; and (3) There is a relative scarcity of blue receptors in 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.

3.5.1.3 A sufficient quantity of green can be added to a pure, highly saturated blue to improve legibility and still have that color identified as blue (as opposed to aqua or bluish-green) by observers.

3.5.2 Recommendations:

3.5.2.1 Highly saturated blue colors with short dominant wavelengths, for example, blue phosphor of CRT by itself, should not be used for alphanumerics or symbols containing fine spatial detail. See appendix for more detailed explanation of saturated blue and dominant wavelength.

3.5.2.2 Adequate legibility should be demonstrated if any blue is used where fine spatial detail is important.

4. NUMBER OF COLORS:

4.1 Considerations:

4.1.1 The use of more than six symbol colors may degrade performance on search, identification and coding tasks due both to poorer discriminability (especially under high ambient light) and a loss of organizational value. With emerging display technologies, the loss of discrimination due to high ambient illumination may become substantially less significant. However, even though colors may maintain their chromaticity specifications under higher ambient illumination, the use of more colors may still adversely affect organizational value.

4.2 Recommendations:

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

4.2.2 In general, no more than six symbol colors should be used to declutter high information content displays. These include white, red, green, yellow (or amber), magenta (or purple), and cyan (or aqua). These six colors plus black, gray, brown, and blue for background shading can be used effectively.

4.2.3 The use of more than these colors is 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. LUMINANCE AND BRIGHTNESS OF COLORS AND BACKGROUND:

5.1 Considerations:

5.1.1 The terms luminance and brightness are often used interchangeably. This practice, however, is incorrect since they actually refer to separate concepts. Luminance can be measured directly with the appropriate instrumentation. This measurement takes both the physical amount of light, known as radiance, and the response of the human eye to light into account. Luminance is, hence, a psychophysical measure. Brightness, however, is an individual's perception of luminance and cannot be measured directly by instrumentation. Such factors as eye adaptation and background luminance can affect the perception of brightness, independent of luminance. Although the two measures are often not in complete quantitative agreement, there usually exists a fairly close qualitative correspondence between the two. For example, an increase in luminance will normally lead to an increase in brightness but the increase in brightness will not be a linear function of the luminance increase.

5.1.2 Voltage changes resulting from adjusting brightness controls can differentially affect the output luminance of the primary phosphors. This results in non-uniform luminance chromaticity changes in the display.

5.1.3 Where color discrimination and absolute color identification are required, a neutral colored (gray) background raster with an intermediate luminance level is better than a completely dark or black background. The exact level of the intermediate luminance necessary for optimum color identification is dependent upon the task of the user and the display conditions. In general, as the luminance of a neutral colored background increases from completely dark, color discrimination and identification improves. However, once the background luminance is the same as the luminance of the colors to be identified, further increases in background luminance result in color discrimination and identification getting worse. Generally, color discrimination and identification are much better when the symbol to background luminance contrast ratio does not exceed about 50:1. In addition, where the range of luminances of the colored images displayed is high, a neutral colored background raster with a luminance in the middle of that range yields superior color identification. For example, if the luminances of colored images on the display ranged from 10 cd/m^2 to 200 cd/m^2, a neutral colored background with a luminance of about 50 cd/m^2 (approximately the geometric mean of 10 and 200) would be appropriate for color discrimination and identification tasks.

The contrast requirements for symbol legibility and color identification are somewhat in conflict. Increased luminance contrast results in increased symbol legibility but decreased color discriminability. However, a balance may be achieved that achieves both good legibility and enhances color discrimination. For example, a symbol to background luminance contrast ratio of about 20:1 would generally yield very good symbol legibility as well as good color discrimination and identification.

At night, when ambient illumination levels are very low, symbols presented on a display are perceived to float about the display surface, especially when symbol density is low. This can be remedied by increasing the luminance of the background slightly so that the background becomes a visible frame of reference, rather than just a dark hole. The background luminance should never be higher than any symbol luminance under these conditions as it might interfere with the observers' dark adaptation.

5.2 Recommendations:

5.2.1 To accentuate differences among colors, differences in the brightnesses of display colors should be used wherever possible. For many displays, however, luminance differences are limited by the hardware and may not be in the desired direction.

5.2.2 Since brightness differences can be used by the operator as a source of information, the relative brightnesses of the colors must track over the total luminance range of the screen. It is also necessary that chromaticity track over the luminance range of the display. The degree of assymetrical tracking is related to the gamma functions of the color primaries and should be characterized for all color display systems. Gamma correction should be employed in the case of significant chromaticity shifts across the useable display brightness range. This is especially important when the luminance is set at low levels during night operation.

5.2.3 A neutral colored background whose luminance can be adjusted by the observer may be necessary. In addition, the use of an automatic brightness compensation circuit is appropriate to eliminate frequent manual adjustments (see Section 6). Since the exact luminance level of the background depends on the task (legibility versus color discrimination, for example) and on the display conditions (nighttime versus high ambient illumination) the display designer must take the considerations listed in 5.1.3 into account. It is false to assume that increased contrast ratios will always lead to increased user performance. As stated in 5.1.3, a balance between the contrast requirements for symbol legibility and color discrimination can be attained by using an appropriate background luminance as per the consideration of 5.1.3.

6. AUTOMATIC BRIGHTNESS/CONTRAST COMPENSATION:

6.1 Considerations:

6.1.1 In general, three types of brightness control are needed to provide a satisfactory automatic compensation system:

a. A manual brightness control to accommodate individual differences in the visual sensitivity of pilots as well as the use of sunglasses or sun visors.

b. An automatic brightness/contrast compensation function that changes the display luminance as a function of changing ambient light levels incident on the display (as detected by an internal light sensor integral to each display).

c. An automatic brightness/contrast compensation function that changes the display symbol-to-background contrast as a function of changing luminance levels in the pilot's forward field of view (as detected by a remote, forward-facing light sensor). The automatic brightness/contrast compensation circuit should ensure that the symbol luminance is sufficient for rapid image recognition for flight critical information, for example, attitude.

6.1.2 In addition to these basic control functions, three other aspects of automatic brightness/contrast compensation systems require consideration. First, the panel-mounted sensor used to measure the level of ambient illumination incident upon the display should have a sufficient field of view to measure all incident angles of ambient illumination that significantly affect the amount of light reflected back from the display surface. Because the percentage of ambient illumination reflected from a display is a function of the angle of incidence, the panel-mounted sensor should have a lens that attenuates illumination as a function of the angle of incidence. The lens off-angle reflectivity characteristics should roughly match those of the display surface, contrast enhancement filter and anti-reflective coating. Second, the sensor used to measure the luminance in the forward field of view should have approximately the same field of view as the cockpit geometry affords the pilot. The forward-facing or remote light sensor should have a lens that attenuates incident light as a function of the square of the cosine of the angle of incidence of light to the sensor. Third, the failure of either automatic brightness or automatic contrast compensation functions should not impair the operation or range of the manual brightness control, nor should such failures enable sudden, extreme increments in display brightness. The design of the failure logic for automatic brightness/contrast compensation systems should provide a graceful reversion to full-range manual control in the event of sensor or system failure.

6.2 Recommendations:

6.2.1 Effective automatic display brightness/contrast compensation systems are necessary for Electronic Instrument Systems. This permits the maintenance of acceptable chromatic differentiation and image brightness under all ambient lighting conditions without the penalty of frequent manual display brightness adjustments during high-workload operations.

7. COLOR SPECIFICATION:

7.1 Considerations:

7.1.1 No one color difference measure that is currently available will give an accurate measure for all tasks involving the use of color.

7.1.2 For tasks involving color discrimination, CIELUV delta E* has been shown to be an effective predictor of performance. Unfortunately, some problems still exist with this measure that preclude its use as a completely precise measure. Hence, it is impossible to specify a satisfactory minimum acceptable color difference at this time. However, CIELUV delta E* can be used to maximize the perceptual differences among colors. Other measures such as CIELAB delta E* can also be used effectively in this task. See Appendix B for color difference formulas.

7.1.3 For tasks involving symbol legibility, CIELUV delta E* is not a good measure and several other methods have been used in an attempt to predict legibility performance. See Appendix B for an example of a proposed legibility measure that has received some empirical validation.

7.1.4 No one 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 CIELUV or CIELAB delta E* may be used as a preliminary selection guide for this purpose.

7.2 Recommendations:

7.2.1 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 must not be added just for aesthetic value. Where a decrement in performance is demonstrated, the use of color should be avoided.

8. EFFECT OF SYMBOL SIZE:

8.1 Considerations:

8.1.1 As symbol 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.

8.1.2 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 B). These correction factors are valuable for re-scaling color differences among colored stimuli that subtend small visual angles such as alphanumerics.

8.2 Recommendations:

8.2.1 As symbol size is reduced, care must be taken to ensure that perceived color differences are maintained.

9. CHARACTERISTICS OF THE USER POPULATION:

9.1 Considerations:

9.1.1 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.

9.1.2 Approximately 1% of Class I pilots have obtained medical waivers for color vision. The severity of their color deficiencies is unknown.

9.1.3 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 quite a bit of variability in color vision performance among pilots that have been classified as having normal color vision.

9.1.4 Beyond congenital color defects, some acquired color defects are also possible. For example, 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.

9.2 Recommendations:

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

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

10. DISPLAY DESIGNER CHECKLIST:

10.1 Considerations:

10.1.1 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 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.

10.2 Recommendations:

10.2.1 In order to demonstrate that the above recommendations have been taken into consideration during the design process, the display designer should document how the following issues have been addressed:

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

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

10.2.1.3 How was the redundancy of color coding implemented?

10.2.1.4 How has chromaticity and brightness tracking been ensured?

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

10.2.1.6 How have the number of colors and the choice of colors for a given format been evaluated?

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

10.2.1.8 How was it ensured that under extreme lighting conditions color degradation will not adversely affect interpretation of the display?

10.2.1.9 How were the color vision characteristics of the intended user population taken into account?

APPENDIX A
DEFINITION OF TERMS

BRIGHTNESS: This is the perception of the intensity of light reflected by an object or emitted by a source of light. It is the perceptual correlate of luminance and, hence, can only be measured via human observations and not via instrumentation.

CHROMATICITY COORDINATES: The chromaticity coordinates for a color are the ratios of each tristimulus value of the color with their sum in the CIE system. The tristimulus values (X,Y,& Z) are based on the amounts of each of three reference lights needed to make an additive color mix that will match the color in question. Since the sum of the chromaticity coordinates always equals 1, only two coordinates need be given to describe a color. This serves to completely describe two psychophysical qualities of every color: dominant wavelength and excitation purity. These correspond to the perceptual qualities of hue and saturation. A third term, the Y tristimulus value is the luminance of the color.

CHROMATICITY DIAGRAM: This is a graphic representation of all possible colors on a two-dimensional diagram. Using two of the three chromaticity coordinates (for example, x and y in the 1931 CIE system, and u' and v' in the 1976 CIE system) each color will plot as a single point on this diagram. Colors of similar dominant wavelength and excitation purity (and correspondingly similar hue and saturation) will plot close to one another. The more widely spaced apart two colors are, the more different they will appear from one another in terms of hue and saturation. Chromaticity diagrams in the CIE system do not account for luminance and hence two color stimuli having the same dominant wavelength and excitation purity but different luminances will plot at the same point. (See Appendix C for example of 1976 CIE Chromaticity Diagram.)

CIE: This is an international organization responsible for color standards. The initials stand for: Commission International de l' Eclairage which translates as International Commission on Illumination.

CIELAB and CIELUV: The 1976 CIE recommendations include two color- difference equations known as the CIELAB and CIELUV equations. Both take luminance contrast, as well as chromatic contrast, into account. There appears to be very little difference in how both equations agree with actual visual data. See Appendix C for the formula equations.

CONTRAST:

(A) Chromatic: the chromaticity difference between two areas such as a symbol and its background. This includes the difference in dominant wavelength and excitation purity between two colors.

(B) Luminance: the relative luminance difference between two areas. It can be defined in several different ways (see formula section).

COLOR VISION DEFICIENCIES: This is a decreased ability to discriminate and identify certain colors, relative to the normal observer. It varies in form according to the particular colors that are confused and in severity according to the magnitude of color differences which cannot be discriminated. It is usually inherited, but may also result from the effects of disease, drugs, and aging. Reduced sensitivity to light of certain colors is sometimes involved.

Color vision deficiencies are categorized in terms of their impact on color-matching and color-discrimination performance. The population can be divided into three groups: trichromats, dichromats, and monochromats. Monochromats are extremely rare and can only discriminate brightness differences. The color confusions which dichromats make are severe. There are two main types of dichromats; those that confuse colors along the red-green axis of the chromaticity diagram, and those that confuse colors along the blue-yellow axis. Trichromats can be divided into normal trichromats who have normal color vision, and anomalous trichromats who have reduced color discrimination ability falling between normal trichromats and the dichromats. Anomalous trichromats may also be categorized as red-green or blue-yellow types according to their patterns of color confusion and may be further categorized according to the severity of their deficiency which may range from mild (near-normal color discrimination ability) to severe (near-dichromatic levels of color confusion). Twenty-five percent of red-green deficients, both dichromats and anomalous trichromats, have a marked loss of sensitivity to red light.

Inherited color vision deficiency affects approximately 8% of the male and 0.5% of the female populations. Approximately 3% of private pilots, 2% of commercial pilots, and 1% of airline transport pilots are known to have some type color vision deficiency. Over 99.9% of inherited color vision deficiencies are of the red-green type. Almost all color deficient pilots would, therefore, be expected to have deficiencies of the red-green type. Acquired color vision deficiencies are of unknown frequency in the population. They are more often of a blue-yellow than the red-green type, may be temporary, and are those due to disease and drug effects. They are usually associated with a significant visual acuity loss. Age-related deficiencies are often associated with reduced sensitivity to blue light.

DOMINANT WAVELENGTH: Dominant wavelength correlates with the hue of a color. It is the spectrum color one would mix with the reference white in order to make a color match. Spectrum colors are those colors that are produced by passing white light through a prism and appear on the boundaries of the CIE Chromaticity Diagrams. See Appendix C for a graphical representation of dominant wavelength.

EXCITATION PURITY: This term represents the relative purity of a color. Monochromatic colors, that is, colors made up of only a single wavelength, have the highest excitation purity while the achromatic white point has the lowest. Excitation purity is defined by the ratio of two lengths on a chromaticity diagram. The numerator is the distance between the color point and the achromatic white point. The denominator is the distance, along the same direction line, from the achromatic white point to the edge of the chromaticity diagram. See Figure A2 as an example. The excitation purity of Color 3, in this figure, is the distance from D65 and Color 3 divided by the distance between D65 and the spectrum locus of 480 nm.

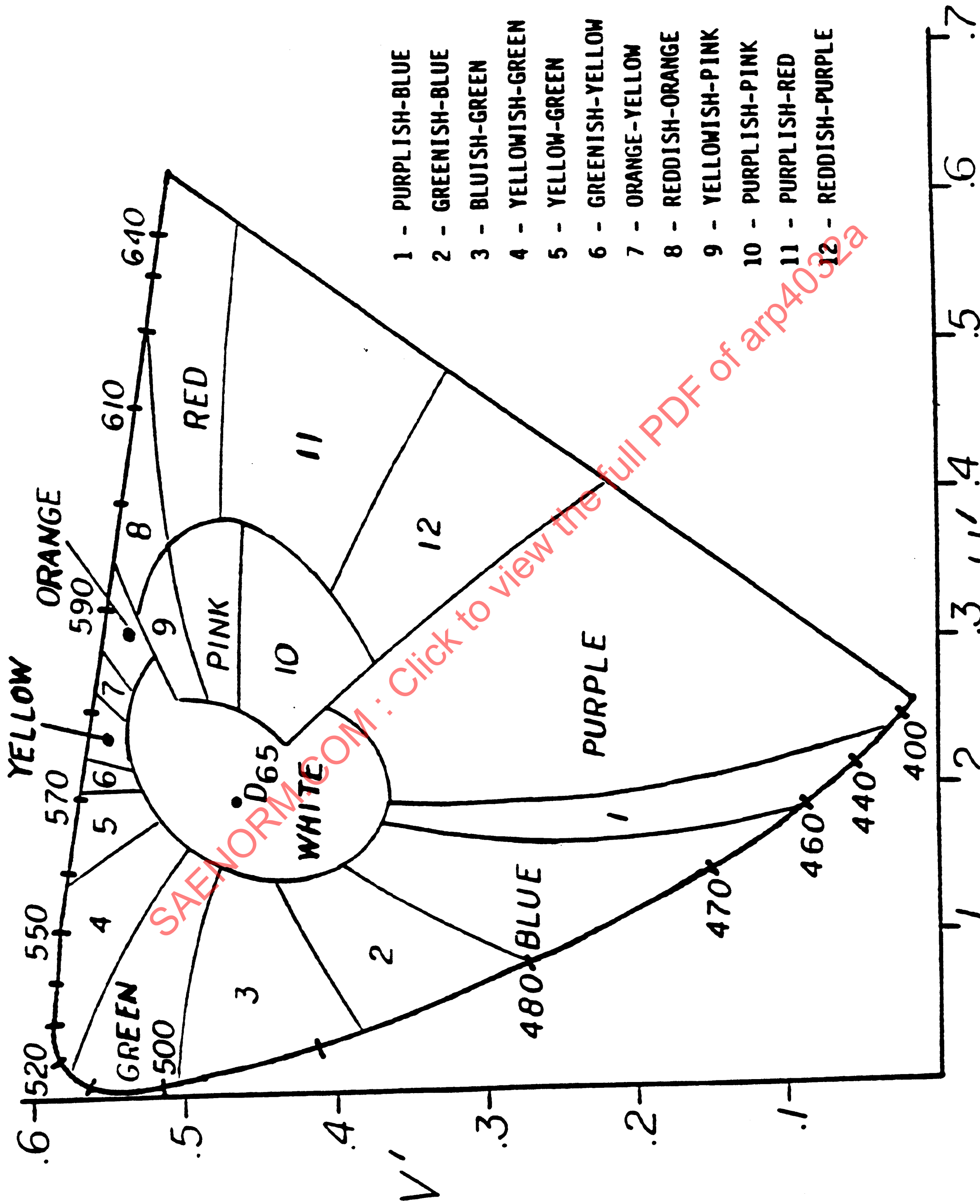

FIGURE A1 - 1976 CIE Chromaticity Diagram

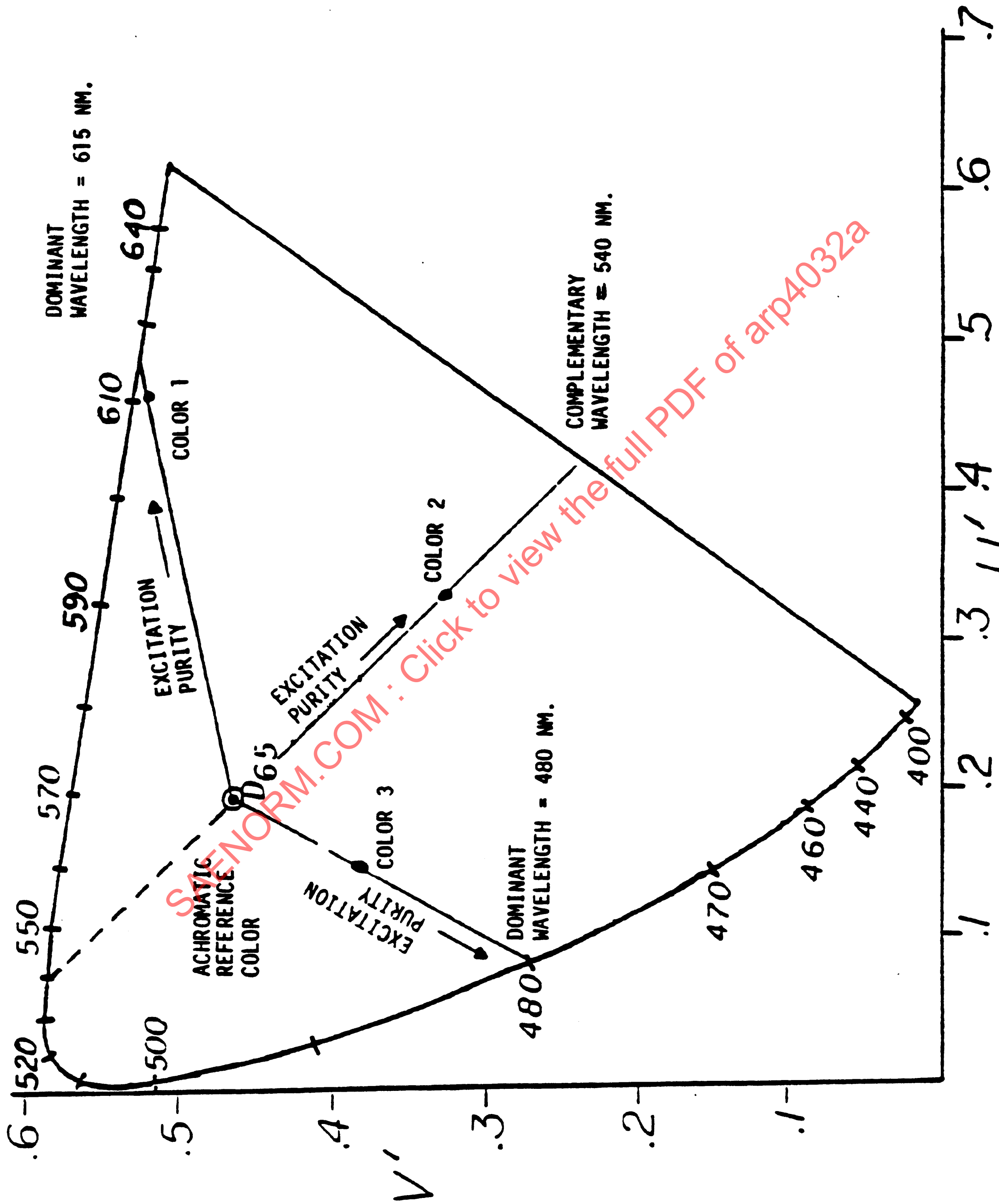

FIGURE A2 - 1976 CIE Chromaticity Diagram

GAMMA CORRECTION: The relationship between video amplifier drive level (voltage) and luminance output of CRT phosphors is nonlinear and different for each primary. This will result in chromaticity shifts of secondary colors as a function of video drive level. Gamma correction is the process whereby correction signals are fed to the video amplifiers to compensate for this and produce stable secondary colors.

HIGH-AMBIENT LIGHTING CONDITIONS: The maximum ambient illumination in a transport aircraft flight deck is at least 86,000 lux (8000 ft-c) while in a bubble-canopy aircraft the value is at least 107,500 lux (10,000 ft-c). These figures, of course, are mediated by such factors as sun altitude, transmittance of the windshields or canopy and angle of incidence of light to the display.

HUE: The quality of light that is characterized by the words green, red, blue, yellow, etc. Hue is independent of both saturation and brightness.

ILLUMINANCE: A measure of the amount of light incident on a surface. This can be measured by instrumentation. The SI units are lumens per square meter (lux), abbreviated as lx. The older, British units are footcandles, abbreviated as ft-c. One footcandle is equal to 10.76 lux.

LIGHT-MODULATING DISPLAY DEVICE: A display device made of material whose reflectance or transmittance changes as a function of the application of an electric field. An example is a liquid crystal display.

LUMINANCE: The amount of light emitted, transmitted or reflected from a display, light source, or other object. It can be measured by instrumentation. The SI units are candelas per square meter (nits), abbreviated as n/t while the older British units are footlamberts, abbreviated as fL. One footlambert is equal to 3.426 nits.

It should be noted that for a perfect Lambertian surface (one that is perfectly made) which reflects 100% of the incident light, one footlambert of luminance will result from one footcandle of illuminance. However, with the same surface, one nit of luminance will result from 3.14 lux of illuminance.

RASTER DISPLAY: A display in which the entire screen is scanned sequentially. This produces less luminance than stroke written images due to the higher writing rate of raster systems.

REDUNDANT CODING: The repetition of information provided in one code by another code. Values of the two codes can be correlated with each other either totally or partially. A multidimensional display combining numeric and color codes provides a good example of redundant coding. If the numeric code consists of the digits one through six and the color code consists of six different colors, then the unique assignment of one of the six colors to each of the six digits would produce complete redundancy. Knowing either the digit or the color would provide complete information. However, if only three colors were used and each color were assigned to two of the six digits, then the color code would be only partially redundant with the numeric code. Knowledge of the color of a symbol would only constrain the range of possible numeric values, thus providing only partial information as to the exact numeric value.

SATURATION: Saturation is the perceptual attribute of excitation purity. It is the deviation of a color from white. Monochromatic colors (spectrum colors) are by definition highly saturated. Highly desaturated colors appear very pale, that is, whitish or grayish. See Appendix C for a graphical depiction of excitation purity.

SELF-LUMINOUS DISPLAY: A display device that generates and emits light from the display face (for example, cathode ray tube).

APPENDIX B
FORMULAS

CIELUV delta E*:

$$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2} \quad \text{(Eq. B1)}$$

where:

$L^* = 116\ (Y/Y_n)^{1/3} - 16$
$u^* = 13\ L^*\ (u' - u'_n)$
$v^* = 13\ L^*\ (v' - v'_n)$

There is currently no standard definition of Y_n for self-luminous displays. One feasible suggestion is to set Y_n to the maximum 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 D_{65} (u'_n = 0.1978 and v'_n = 0.4684)

$$u' = 4X / (X + 15Y + 3Z) \text{ or } 4x / (-2x + 12y + 3) \quad \text{(Eq. B2)}$$

$$v' = 9Y / (X + 15Y + 3Z) \text{ or } 9y / (-2x + 12y + 3) \quad \text{(Eq. B3)}$$

CIELAB delta E*:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad \text{(Eq. B4)}$$

where:

$L^* = 116\ (Y/Y_n)^{1/3} - 16$
$a^* = 500\ [(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$
$b^* = 200\ [Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$
X_n, Y_n, & Z_n = the tristimulus values of the reference white