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Air Traffic Control Display Standard: A Standardized Color Palette for Terminal Situation Displays

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16. Abstract

As the Federal Aviation Administration moves toward the implementation of the Next Generation Air Transportation System, there is a need to increase commonality and standardization across Air Traffic Control (ATC) displays. Increased standardization will reduce development costs and training requirements, as well as ensure that new ATC systems follow human factors guidelines and best practices. The Air Traffic Control Display Standard provides specific design standards for ATC displays that are grounded in human factors research and lessons learned from the field. Previous guidelines on the use of color lacked specificity and were difficult for system developers to implement. This document provides specific standards for the use of color on ATC situation displays in the terminal domain. We developed the standards by measuring the colors used on existing systems to determine whether the colors met human factors guidelines for attention, identification, segmentation, and text legibility. When existing colors did not follow the guidelines, we developed alternatives. In this report, we provide a standard color palette. We list individual display elements (e.g., datablocks, radar targets) and specific color names and coordinates for each element. We also provide guidance for system developers and vendors to help them implement the standard color palette on their systems.

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Executive Summary

As the Federal Aviation Administration (FAA) moves toward the Next Generation Air Transportation System (NextGen), new tools and capabilities will be added to Air Traffic Control (ATC) displays. There is a growing need for standardization among systems both within and across ATC domains. Standardization allows system developers to avoid "reinventing the wheel" for each new system or upgrade. It allows them to reuse the lessons they have learned when developing one system on future systems. Standardization also increases the flexibility of the overall ATC system by allowing users to move more readily between systems while also reducing the chance for human error. Finally, increased standardization encourages the use of human factors guidelines and standards.

In this report, we provide a standardized color set for use on terminal ATC situation displays. Color is used on displays for three primary purposes: attention, identification, and segmentation (Xing & Schroeder, 2006). First, color is used to indicate changes of status to draw or capture attention. For example, the datablocks for aircraft involved in a conflict situation may appear in red text to distinguish them from aircraft that are not. This draws the controller's attention to aircraft involved in a potentially unsafe situation. Second, color is used to identify and classify information. For example, primary targets may appear in blue and beacon targets may appear in green. This allows controllers to easily determine the types of targets they are trying to separate. Third, color is used to segment information and reduce clutter. For example, areas of light precipitation may appear in gray to distinguish those areas from the black background. This allows controllers to determine where the precipitation is located. When used appropriately, color can increase situation awareness, reduce search time, and direct attention. However, if not used correctly, color use can impair human performance rather than enhance it.

Vendors developed the main terminal situation displays, the Common Automated Radar Terminal System (CARTS) and the Standard Terminal Automation Replacement System (STARS), independently, without specific FAA standards regarding the use of color. This resulted in inconsistent color coding between the two systems and made system development and testing more complicated and time consuming. The inconsistencies also made it more difficult to standardize procedures across CARTS and STARS facilities because the two systems used different colors for important display elements (e.g., datablocks, radar targets). In recent years, FAA Order 7210.3, paragraph 3-10-1, has reduced the inconsistencies between CARTS and STARS. However, the order is not specific with regard to color coordinates and does not address all of the display elements that appear on the two systems. In addition, the order does not provide guidance on additional colors that future systems or tools may use.

The standard color set provided in this report lists individual display elements and provides corresponding color names and specific color coordinates. Established human factors guidelines and lessons learned from the field influenced the selection of these colors. We measured the colors used on CARTS and STARS to evaluate whether the existing colors followed the guidelines for attention, identification, and segmentation (FAA, 2007; Xing, 2007b). In cases where the existing colors did not follow human factors guidelines, we developed and tested alternatives. In this report, we also provide guidance on how vendors, system developers, and the program office can use this standard color set and apply the rules effectively. We have designed the standard color set to be directly usable by system developers when selecting and implementing colors for terminal ATC systems.

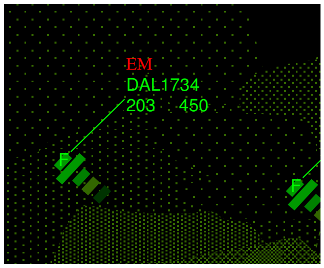
We also believe that this report can serve as a model for developing color standards for other ATC domains and display types. Many systems are in development as part of NextGen and will become part of the controller toolbox of the future. In the near term, many other systems are nearing deployment, including systems for surface surveillance, information display, and weather. Each of these systems currently maintains its own color palette with little or no standardization across systems. Our immediate goal is for individual systems to use color consistently and follow human factors guidelines. Our interim goal is for all systems within a domain to use color consistently across systems, especially systems that a single individual uses together. Our ultimate goal is for all systems in all domains to use color consistently while also following human factors standards.

1. INTRODUCTION

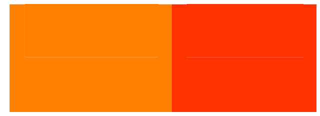
Systems and designers use color for three primary purposes: to indicate changes of status so as to draw or capture attention, to identify and classify information, and to segment information and reduce clutter (Xing & Schroeder, 2006). When used appropriately, color can increase situational awareness, reduce search time, and direct attention. However, if not used correctly, inconsistent or suboptimal color use can impair performance and increase the likelihood of errors. Not all color effects are intuitive, and what people like does not always correspond to an increase in performance.

A lack of standardization in the colors used on different display systems increases training and documentation requirements. People who use more than one display system at a time must work harder to remember color meanings for each display. Negative transfer, when a user mistakenly applies knowledge from one system to another, may occur. This is especially problematic when two systems use the same color to mean different things. Some effects do not disappear or diminish with extra training or experience because attributes of the human perceptual system govern these effects. Additionally, designers must take into consideration operational use conditions when evaluating colors. They need to conduct tests on the selected color palettes under operational conditions to validate their effectiveness and usefulness in all settings. They also need to conduct these tests for different viewing angles, color of ambient lighting, levels of illumination, display brightnesses, and foreground/background combinations. Many systems are in development as part of the Next Generation Air Transportation System (NextGen) and will become part of the controller toolbox of the future. In the near term, many other systems are nearing deployment, including systems for surface surveillance, information display, and weather. As the Federal Aviation Administration (FAA) moves toward NextGen, there is a growing need for standardization.

There is a set of agreed-upon human factors DO's and DON'Ts that designers should apply when designing color palettes for display systems (Ahlstrom & Longo, 2003; Cardosi & Hannon, 1999; Xing, 2006a, 2006b, 2007a, 2007b). *Color coding should always be redundant with another form of coding*. For example, if red text within a datablock is an emergency indicator, the system could redundantly code this information by using the text "EM" as an abbreviation for emergency (see Figure 1a). The Common Automated Radar Terminal System (CARTS) and the Standard Terminal Automated Replacement System (STARS) currently employ redundant color coding for safety-related information, such as conflict alerts. *Color coding should be consistent*. If a display uses yellow datablocks to indicate pointouts, which is attentional coding, the display should not also use yellow to indicate ghost targets, which is identification coding. *Color codes should use colors that are distant on the color scale*. Users will make more errors trying to distinguish between orange and reddish-orange (see Figure 1, b1) than between orange and blue (Duncan & Humphreys, 1989; see Figure 1, b2). *Color codes should use colors with clear, obvious names* because users will remember red and blue better than rose and aqua. *Displays should maximize contrast for text* (e.g., white on black, yellow on blue; see Figure 1c) because when the contrast is low, text is hard to read (e.g., blue on black, green on blue; see Figure 1d). In almost all instances, *color codes should follow conventional meanings*. For instance, green should denote positive states and red should denote negative ones (see Figure 1e). Lastly, *pure, bright, saturated colors should primarily be used as highlights, not as indicators of normal states*.

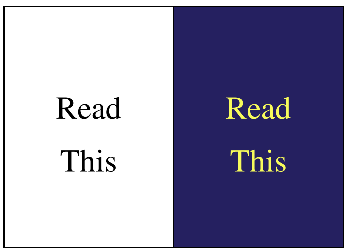


a. Using redundant coding (e.g., EM)

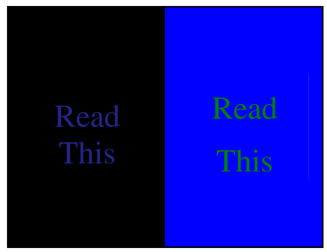


b1. Colors not distant on the color scale

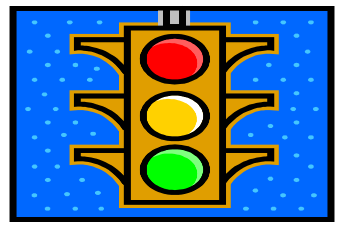
b2. Colors distant on the color scale



c. Using maximal text color contrast



d. Using nonmaximal text color contrast



e. Using conventional meanings

Figure 1. Examples of color "DO's and DON'Ts."

1.1 Purpose

The purpose of this study was to develop a standardized color palette for terminal situation displays and determine the most effective colors to use for various display elements, such as targets and datablocks. To accomplish this, we measured selected colors on two current Air Traffic Control (ATC) displays and two Commercial-Off-The-Shelf (COTS) displays using a spectraphotometer to identify which Red, Green, and Blue (RGB) values on a given monitor produced which Commission Internationale de l'Éclairage (CIE) values. We then evaluated all measured colors against the set of FAA baseline requirements (FAA, 2007; Xing, 2007b) for compliance with those guidelines.

Although most standards provide system designers with high-level requirements, the system designers often have difficulty applying them in a specific context. In addition, because high-level requirements are so general, we have found that designers often interpret them in many different ways, which may not lead to the development of acceptable or consistent user interfaces. To develop a standardized color palette for terminal situation displays, we believed that we needed to provide much more detail than found in a typical standard. Consequently, this standard is reported at the level of detail typically found in a specification document.

1.2 Background

Across the FAA, different ATC systems and products use different color sets. Since the FAA introduced color displays in the 1990s, each ATC program has been responsible for developing its own color set and coding techniques. Engineering Research Psychologists (ERPs) helped develop some of the color sets used currently on terminal situation displays (Allendoerfer, Yuditsky, Mogford, & Galushka, 2005), but most were developed independently and without specific guidelines on the use of color. Due to this lack of specific guidance, developers of different FAA software often have to create and develop color sets, "reinventing the wheel" each time they develop a new system or make changes to an existing system. Although individual programs have learned lessons about ways to use color effectively, they sometimes do not communicate these lessons to other programs. This lack of standardization increases development and testing costs for FAA acquisition programs.

ATC systems often use color as an attentional cue, enabling controllers to distinguish among different display items. ATC systems may use color as status indicators that can inform the controller whether a system is functioning properly. They may also use color to classify or categorize; for example, to indicate whether a particular aircraft is owned or unowned. Lastly, ATC systems may use color for segmentation or demarcation, as when they use colors to mark sector boundaries. Developing a standard color set that applies to all FAA ATC systems in all domains is a major undertaking. This report focuses on one domain and one display type: the primary terminal ATC situation display. Currently, the most common situation displays in the terminal environment are the ARTS Color Display (ACD) and Remote ARTS Color Display (R-ACD) of CARTS and the Terminal Controller Workstation (TCW) and Tower Display Workstation (TDW) of STARS.

Different programs and vendors independently developed the original color sets used on CARTS and STARS. This led to inconsistent color coding on the two systems, which made system development and testing more complicated and time consuming. The inconsistencies, such as the use of different colors for important display elements (e.g., datablocks, radar targets), also made it difficult to standardize procedures across facilities. In recent years, amended FAA Order 7210.3, paragraph 3-10-1, has reduced the inconsistencies between the terminal situation displays. The amended order states, for example, "Point out identifier blinking or steady shall be yellow" (FAA, 2008). The amended order is clearly an improvement, but it still does not specify color coordinates and does not address all the display elements on the two systems.

Several other FAA guidelines exist for using color on ATC displays, including Cardosi and Hannon (1999) and Xing (2007b). These documents provide human factors guidelines for using color and offer recommendations and broad requirements. However, they are not tailored or specific enough to be included as requirements in an FAA specification for future acquisition programs. In particular, the existing guidelines do not provide specific color values for most elements appearing on ATC displays. If a system specification requires specific colors for specific display elements (e.g., "Datablocks **shall** be green.") but does not provide specific color values, system developers do not know which of the hundreds or thousands of possible colors to choose. For example, if datablocks are required to be green, each system vendor is free to implement any color values it chooses, so long as the resulting color appears "green." However, some greens will provide satisfactory human factors performance and others will not. There are also a variety of international standards related to the use of color (see Appendix A), and we refer the interested reader to these documents for more detailed information on color standardization.

The goal of this project is to develop detailed and practical guidance for standardizing color palettes across terminal ATC products for use by Terminal Radar Approach Control (TRACON) and tower controllers. Product leads, program offices, and vendors will be able to refer to these color palettes when developing new terminal ATC products. Use of these palettes should reduce developmental costs, create satisfied users, and, in the long term, lead to a more standardized National Airspace System (NAS). Although our initial effort focuses on terminal situation displays, eventually all terminal systems should be included. Our intent is to provide a standard color set with corresponding CIE values. ERPs, designers, and developers of tower or TRACON products should be able to tailor their selection of colors from this set to meet the specific user requirements for any system under development. The standard color set will be effective, easy to use in all operational environments, and should not create any unintended human factors consequences, such as an increase in workload.

Although this standard uses device-independent CIE coordinates to specify color, computers use RGB values to display color. Human factors guidelines must be careful about providing only CIE coordinates in a color standard. If a color standard provides only CIE coordinates, system developers may not know which RGB values they should implement to produce the required CIE coordinates. If system developers perceive the standard to be difficult to use in the design phase, or if they perceive it as too difficult or expensive to test, they are less likely to use or follow it. For a color standard to be maximally useful, the standard should be directly usable by system developers when they are selecting and implementing colors.

Therefore, this standard will also provide corresponding RGB values for all colors, as tested on several COTS monitors. The expectation is that vendors will use the provided RGB values as starting points. If those RGB values, used on the display of their choice, fail to produce the required CIE values, vendors will need to adjust the RGBs accordingly or select a different display.

Finally, this document should serve as a model for developing color requirements for other ATC domains and display types. Many new systems are nearing deployment, including systems for surface surveillance, en route situational display, and weather display. Each one currently uses its own color palette, with limited standardization across systems. Our goal is for all platforms to use colors consistently, while ultimately standardizing colors across all NAS systems.

1.2.1 Introduction to Color

We can characterize color using a variety of different color spaces or coordinate systems, including the CIE and the standardized Red, Green, and Blue (**sRGB**) color spaces (Ford & Roberts, 1998). Different color spaces have different applications. The Hue, Saturation, and Luminance color space is the most intuitive color space, and it describes how people perceive and name colors. **Hue** is the characteristic of a color that distinguishes one color of the rainbow from another. For example, the color red is a different hue than the color blue. **Saturation** characterizes a color's purity. As you add varying amounts of a color's opposite or complementary color to it, the color becomes desaturated. Desaturated colors migrate towards a neutral gray. People typically characterize desaturated colors as pastels. For example, the color pink is an example of desaturated red. Lastly, **luminance** is the lightness or brightness of a color, ranging from white to black. Less luminant colors are darker. For example, the color *eggplant* is the same hue and saturation as purple but has such low luminance that it appears almost black.

The CIE color system is the most useful color space system for our purposes and accounts for human perception. However, there are many different CIE color spaces, including CIE CAM02, CIE CAM97, CIE 94, CIE YUV, CIE Lab, CIE Luv, and CIE xyY. Each one varies in its ability to represent perceived color differences accurately. Common to all of these systems is the CIE 1931 XYZ color space (see Figure 2; see Ford and Roberts [1998], for an in depth description of the CIE systems and the transformations required to go from one CIE coordinate system to another). To date, there has been limited objective research evaluating *which* CIE color system is optimal in which situations. Even when experimental evidence favors one system over another, the benefits are often minimal and can vary or reverse, depending on environmental factors (Fairchild, 2005). Although CIE CAM02 and CIE CAM97 are currently favored in graphics and color matching, for our purposes, the derived benefits of using those models do not outweigh their computational complexity and, therefore, do not justify their use. Consequently, we have chosen to use the most well-established color space, CIE Luv (see Figure 3), which imitates the logarithmic response of the eye and the CIE xyY color space, which is derived from the CIE XYZ tristimulus values.

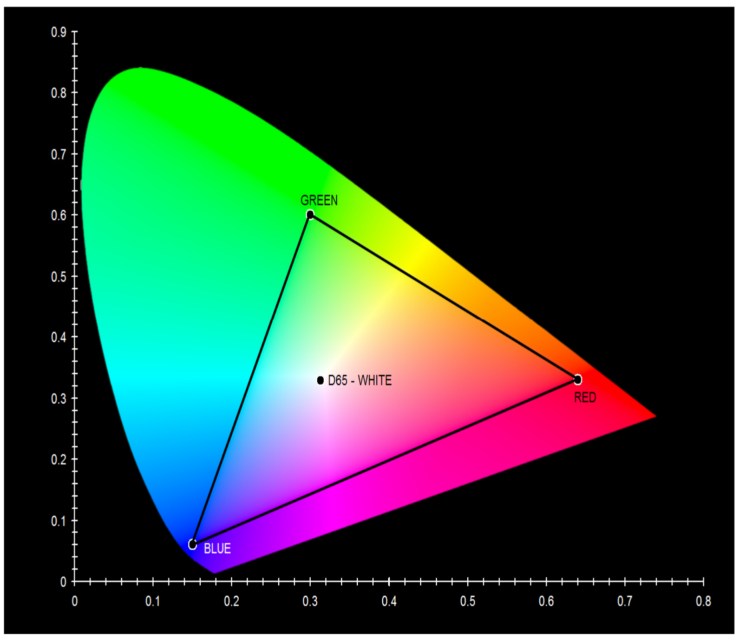


Figure 2. CIE 1931 xy chromaticity diagram with sRGB gamut and D65 white point indicated.

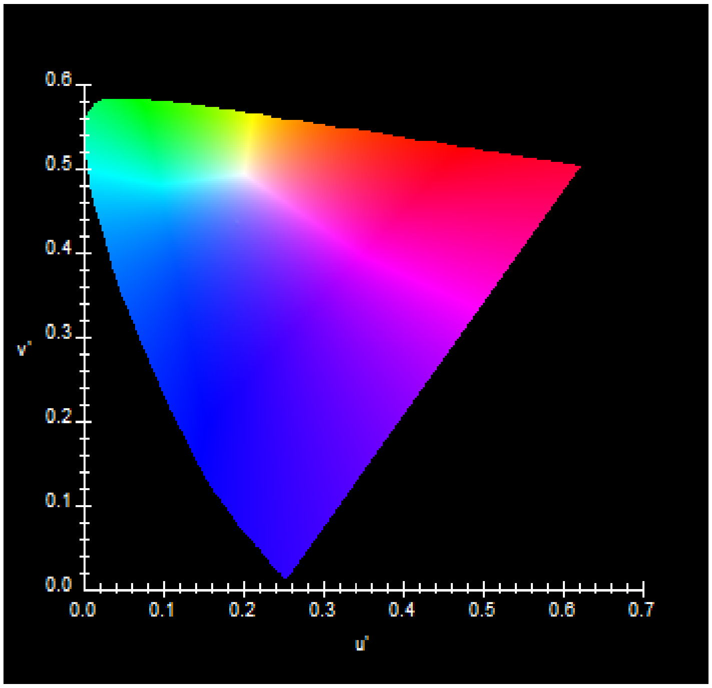


Figure 3. CIE 1976 u′v′ chromaticity diagram.

In the CIE XYZ and CIE xyY color spaces, Y represents the luminance. The chromaticity (hue and saturation), specified by x and z are derived from XYZ using Equations 1 and 2.

$$x = \frac{X}{X + Y + Z} \tag{1}$$

$$y = \frac{Y}{X + Y + Z} \tag{2}$$

Then u′ and v′ for CIE Luv can be computed from x and y using Equations 3 and 4.

$$u' = 4x/(-2x + 12y + 3) \tag{3}$$

$$v' = 9y/(-2x + 12y + 3) \tag{4}$$

Although CIE Luv color space accurately measures color and represents those measurements in a way that mimics the transformations made to colors by the human visual system, it does not always tell us about actual color appearance (Ford & Roberts, 1998). Environmental factors and surrounding colors may affect color appearance. For example, people may perceive a color presented under natural light differently than the same color viewed under artificial light. Also, glare or reflections produced by light reflecting off the surface of glass may affect how people perceive colors on a computer screen or through a window. Differences in individual visual capabilities, such as visual acuity, color blindness, and contrast sensitivity all influence the perception of color, as can the use of personal devices like glasses or sunglasses.

Computer graphics use the RGB color system. The RGB color system characterizes a given color by the amount of red, green, and blue light needed to produce that color. Most modern graphic systems use 24-bit RGB color, also known as TrueColor, which provides more than 16 million (i.e., 16,777,216) possible resulting colors. In such systems, there are 256 possible values for each of the three primary colors that in different combinations produce all of the colors on a computer monitor. Red is designated by (255, 0, 0) – that is, 255 "units" of red, 0 of blue, and 0 of green – blue is designated by (0, 255, 0), and green is designated by (0, 0, 255). However, the RGB color space does not represent perceived color differences in perceptually useful coordinates. That is, color differences that humans perceive to be equidistant may not be equidistant in an RGB color space. Additionally, RGB colors are device dependent. The color produced by a set of RGB values on one monitor, may not be the same as the color produced by the same set of RGB values on a different monitor. Equipment factors, such as the calibration of a monitor, the manufacturer, the type of technology (e.g., Liquid Crystal Display [LCD], Digital Light Processing [DLP], or Cathode Ray Tube [CRT]), the age of equipment, and the monitor settings, may influence the color appearance for a given set of RGB values on a specific monitor. Using sRGB colors, which are standardized and device independent, minimizes these differences (see triangle in Figure 2). Theoretically, this means that sRGB values on all sRGB compliant LCDs, DLPs, and CRTs should appear the same. However, unless you calibrate sRGB monitors appropriately they may, like other monitors, not produce standardized colors (Bodrogi, Sinka, Borbely, Geiger, & Schanda, 2002; Rehák, Bodrogi, & Schanda, 1999).

One additional problem with the sRGB compliant monitors is that they cannot produce colors that lie outside of the sRGB gamut (see triangle in Figure 2). Although it might seem that a monitor that can produce more than 16 million colors would be sufficient for most purposes, we are aware of at least one problem related to its inability to produce certain colors. If a tower controller fails the standard color vision test, they must pass a test that asks them to discriminate the red and green used as wing tip lights, known as Aviation Red and Aviation Green. However, no monitor can produce Aviation Red and Aviation Green because they fall outside the sRGB color space. Although tower controllers who pass this second-tier test demonstrate the ability to discriminate the red and green used as wing tip lights, they have not demonstrated an ability to discriminate reds and greens that lie within the sRGB gamut. This second tier test was acceptable when controllers did not have color monitors, but could lead to serious problems as the use of color on ATC displays increases. As a consequence, the Office of Aerospace Medicine Civil Aerospace Medical Institute has had to develop a new color vision test to ensure that tower controllers can discriminate the red and green used for lights as well as sRGB compliant reds and greens.

1.2.2 History of Color Palettes for STARS and CARTS

From 1998 to 2006, the STARS Computer-Human Interface (CHI) Working Group selected and validated the colors initially used in STARS. The colors were prototyped and validated in a number of test and simulation activities (Allendoerfer et al., 2005) at the FAA Research Development and Human Factors Laboratory. In the same period, the FAA developed and fielded CARTS, using a color palette defined by the program office and the vendor.

In 2006, the FAA Air Traffic Organization-Terminal Division (ATO-T) standardized the functionality and use of many colors by changing the color palettes of the STARS TCW and the CARTS ACD. Both systems currently use almost identical color-coding strategies for the main display elements (e.g., background, datablocks, alerts, and pointouts) and are similar on many other elements (see Table 1). For example, both STARS and CARTS color code datablocks to indicate aircraft ownership. Datablocks owned by the controller are white, and those owned by other sectors are green. Despite a lack of human factors involvement in its development, the CARTS CHI color palette is quite good. Controller performance with this palette has been consistently acceptable, and the largest TRACONs have used CARTS ACDs successfully since 2000.

Table 1. STARS TCW and CARTS ACD Display Elements and Colors/RGB Values

Function	STARS TCW Color	STARS TCW RGB Values	CARTS ACD Color	CARTS ACD RGB Values
Background	Black	0,0,0	Black	0,0,0
Datablocks Owned	White	255,255,255	White	255,255,255
Alert Datablocks/EM	Red	255,0,0	Red	255,0,0
Pointout Identifier	Yellow	255,255,0	Yellow	255,255,0
Limited/Partial Datablocks Unowned	Green	0,255,0	Green	0,255,0
Beacon Target Extent	Green	0,255,0	Green 4	0,139,0
List Titles, Lists, Preview, System Status	Green	0,255,0	Green 4	0,139,0
Search Target Symbol	Search Target Blue	30,120,255	Deep Sky Blue	0,191,255
History Trails 1	Blue	30,80,200	Royal Blue 1	72,118,255
History Trails 2	Blue	70,70,170	Blue[b]	–
History Trails 3	Blue	50,50,130	Blue[b]	–
History Trails 4	Blue	40,40,110	Blue[b]	–
History Trails 5	Blue	30,30,90	Blue[b]	–
Compass Rose	Dim Gray	140,140,140	Gray 56	143,143,143
Maps A & B	Dim Gray	140,140,140	Gray 56	143,143,143
Range Rings	Dim Gray	140,140,140	Dark Gray	96,96,96[c]
Predicted Track Line	White	255,255,255	NA[a]	NA[a]
MinSep Line	White	255,255,255	NA[a]	NA[a]
SA/MI	Yellow	255,255,0	NA[a]	NA[a]
Ghost Target	Yellow	255,255,0	Yellow	255,255,0
Geographic Restriction	Yellow	255,255,0	Yellow	255,255,0
Range Bearing Line	Green	0,255,0	Green	0, 255,0
Coord. Rundown List	Green	0, 255,0	Green	0, 255,0
Weather 1	Dark Gray Blue	57,115,115	Dark Gray	96,96,96[c]
Weather 2	Dark Gray Blue	57,115,115	Dark Gray	96,96,96[c]
Weather 3	Dark Gray Blue	57,115,115	Brown	172,90,0
Weather 4	Dark Mustard	124,124,64	Brown	172,90,0
Weather 5	Dark Mustard	124,124,64	Reddish brown	204,48,0
Weather 6	Dark Mustard	124,124,64	Reddish brown	204,48,0
TPA (J-rings and Cones)	TPA Blue	30, 20,255	TPA Blue	30, 20,255
Weather in Lists	Cyan	0,255,255	NA[a]	NA[a]

Note. EM = Emergency; SA = Suspect Aircraft; MI = Military Intercept; and TPA = Terminal Proximity Alert. [a]Predicted Track, Min Sep, and SA/MI are not on CARTS. [b]Although the CARTS History Trails (blues) follow a similar pattern as the STARS History Trails, we were unable to obtain the RGB values (as indicated by the dashes), so we did not test for these colors. [c]This color is similar to the tested color (Gray 38), but it differs slightly in its RGB values.

1.3 ATC Color Standards and Requirements

Xing (2007b) developed a set of guidelines that provides general rules for using color on ATC displays. Her guidelines served as the basis for a set of FAA baseline requirements (FAA, 2007), which we will refer to hereafter as HF-STD-002. The guidelines (FAA, 2007; Xing, 2007b) state that color coding is used for attention, identification, and segmentation. We will use these guidelines and requirements for attention, identification, and segmentation to evaluate colors currently used on STARS and CARTS. This section briefly describes those requirements.

1.3.1 Attention Requirements

System designers must follow the attention requirements 1 to 3 when using color for attention. Because the purpose of this study is primarily to select colors for terminal displays, in this report we will only evaluate colors for compliance with attention requirements 1 and 2. These requirements relate to factors that can be measured using a spectrophotometer. Because we are developing a generic color set, we cannot evaluate colors for compliance with requirement 3 because its application is context dependent. In general, when the evaluation of compliance with a specific requirement required a specific context, we did not evaluate colors for compliance with that requirement.

1. When using color for attention, the luminance (*L*) of the item of interest (i.e., the target) shall not be less than the luminance of any other displayed items (i.e., the distractors; HF-STD-002, 3.2.1.1).
2. When using color for attention, the luminance of the target shall be 20 candelas per square meter (cd/m^2) greater than the luminance of the distractors (see Equation 5; HF-STD-002, 3.2.1.2).

$$L_{difference} = L_{target} - L_{distractor} \tag{5}$$

   However, if the luminance difference is less than 20 cd/m^2, the absolute chromaticity (*c*) difference between the target and the distractors shall be greater than .24 in CIE uniform chromaticity coordinates (see Equation 6).

$$c_{difference} = \sqrt{(\Delta u')^2 + (\Delta v')^2} \tag{6}$$

   The values of u' and v', used in equation 6, can be calculated from a color's hue (x and y) using Equation 3 and Equation 4 (see Xing, 2007b for more detail).

3. There will be fewer than five distractor colors used on the display (HF-STD-002, 3.2.1.3).

1.3.2 Identification Requirements

For identification, there are four requirements that system designers must follow. We will only evaluate color for compliance with identification requirements 2 and 4.

1. Colors used for identification need to be named reliably and consistently (HF-STD-002, 3.2.2.1).
2. When using nonbasic colors for identification (e.g., mauve, taupe), the chromaticity difference between colors should be greater than .04 in CIE uniform chromaticity coordinates (see Equation 6; HF-STD-002, 3.2.2.2).

3. No more than six colors should be used for identification purposes (HF-STD-002, 3.2.2.3).
4. When using color for identification, the luminance difference between colors shall be less than 20 cd/m^2 (see Equation 5; HF-STD-002, 3.2.2.4). However, the actual luminance must be high enough to allow controllers to reliably detect the colors when they reduce the brightness of their monitors (Ahlstrom & Arend, 2005).

1.3.3 Segmentation Requirements

For regional segmentation, which is segmentation of contiguous regions, and for pattern segmentation, which is segmentation of noncontiguous regions, there are three requirements (FAA, 2007; Xing, 2007b). We will only evaluate colors for compliance with segmentation requirements 1a, 1b, and 2.

1a. When using color for regional segmentation, the chromaticity difference (see Equation 6) between an object and its surrounds must be greater than .004. This requirement also states that as an alternative to having a chromaticity difference greater than .004, the luminance ratio (see Equation 7) shall be greater than 5% (HF-STD-002, 3.2.3.1). Meeting the chromaticity difference requirement is more effective than meeting the luminance ratio requirement.

$$L_{ratio} = \frac{\left|L_{object} - L_{surrounds}\right|}{L_{object}} \tag{7}$$

1b. When using color for pattern segmentation, the chromaticity difference (see Equation 6), shall be greater than .012. As an alternative, the luminance ratio (see Equation 7) shall be greater than 20% (HF-STD-002, 3.2.3.1).

2. When using color for pattern or regional segmentation, the luminance difference (see Equation 5) between colors shall be less than 20 cd/m^2 to give regions the same visual salience (HF-STD-002, 3.2.3.2).
3. When using color for pattern or regional segmentation, an object that is to be segmented shall use no more than two colors unless textures are also used for the differentiation of regions (HF-STD-002, 3.2.3.3).

1.3.4 Text Legibility Requirement

We also will evaluate whether colors meet the text legibility requirement. For this requirement, the luminance (i.e., Michelson) contrast (see Equation 8) between the text and the background should be greater than 30%. However, the contrast should be trimmed to 0 if the luminance of either the text or the background is less than 12 cd/m^2 (HF-STD-002, 3.3.1).

$$L_{contrast} = \frac{L_{text} - L_{background}}{L_{text} + L_{background}} \tag{8}$$

For all colors used for attention, identification, segmentation, and text on STARS and CARTS, we tested whether they met their corresponding requirements.

1.3.5 Additional Color Requirements

In addition to the aforementioned requirements, colors used on ATC terminal displays also should meet the following seven requirements. However, because our purpose is to develop a generic color set, we will only evaluate colors for compliance with these requirements when compliance with these requirements is relevant in a generic context.

1. Color coding should be accompanied by redundant coding (HF-STD-002, 3.3.2), especially when coding critical information. Dual coding helps mitigate problems related to the use of displays by color deficient individuals, under different lighting conditions, or in other situations that can negatively impact accurate color perception.
2. The number of colors used in one display mode for identifying data categories should be fewer than seven (HF-STD-002, 3.3.3).
3. No more than three sets of colors should be used to identify categories of information (HF-STD-002, 3.3.4). Using many colors and multiple coding systems can create undue workload and should be avoided.
4. Color use shall always be consistent with its standard meaning (HF-STD-002, 3.3.5). For example, a system should reserve red to be used for emergencies or to draw attention. Color use that conflicts with its standard meaning or population stereotype can cause confusion and increase response times.
5. All coding used for attention and identification shall be correlated (HF-STD-002, 3.3.6). That is, each system should use each color for a unique purpose and all information with that purpose shall be coded in that color. When coding is uncorrelated, users may make mistakes in determining correct color meanings.
6. For information that needs to be instantly integrated or related, the system should use the same color (HF-STD-002, 3.3.7). Not using the same color can increase the amount of time it takes a user to apprehend, relate, or integrate information.
7. A system should avoid the simultaneous onset of multiple salient colors requiring attention (HF-STD-002, 3.3.8). Too many alerts in too many colors activating at the same time can lead to a decrease in attention to critical, but nonalerted, display elements. It can also increase the amount of time it takes to identify the most critical of the many activated alerts.

2. METHOD

2.1 Equipment

We measured the colors on two monitors currently in use in ATC facilities; we used the Barco 2K (MDP-471) LCD Display and the General Digital (90-850-021-1) Sunlight Readable RGB Industrial Display.[1] The Barco 2K is a 28″ (2K x 2K) LCD display and is the current DSR display at en route facilities. It is a possible candidate for use as a replacement display at

[1] Due to difficulties in calibrating and measuring some colors on the Sony 2K, we excluded the Sony 2K from our analyses.

terminal facilities. The General Digital display is a 20.1″ sunlight readable LCD monitor used by the FAA as the STARS TDW. In addition, we measured the colors on two COTS LCD displays: one Eizo Flexscan (S21411W-U) 24.1″ LCD monitor and one Samsung Syncmaster (244T) 24.3″ LCD monitor. We chose one because it is a high end display used by graphic artists (the Flexscan) and the other because it is a moderately priced unit known to have good color reproduction capabilities (the Syncmaster).

We measured the monitors using a calibrated Photo Research® Inc. PR-650 SpectraScan® SpectraColorimeter™ (also known as a spectraphotometer) and standard factory settings. We used the spectraphotometer to measure Y or luminance in candelas per square meter (cd/m^2), the xy chromaticity coordinates using the standardized CIE 1931 2° observer, the u'v' chromaticity coordinates using the CIE 1976 2° UCS observer, and the CIE La*b* values (Photo Research, 1999). For computational purposes, we used a standard illuminant of D65 as a reference illuminant because this is the standard illuminant for monitors (Hoffman, 2006). Because measuring displays can be complicated, we refer the interested reader to Kelly (2001, 2006) and to Brown and Ohno (1998) for more information.

2.2 Data Collection Procedures

We first measured eight standard colors, three colors specific to CARTS,[2] nine colors specific to STARS, and eight additional colors used by Xing (2006b). When it was possible to adjust the monitor brightness, we measured the colors at 100% and 60% monitor (hardware) brightness. Because STARS and CARTS allow controllers to adjust the brightness of individual display elements, we also measured the colors on all monitors at 100% and 60% software brightness. To simulate the software brightness controls, we multiplied the RGB values by .6 to obtain the RGB values for 60% software brightness. This corresponds to the transformation used by system software to implement software brightness controls. For those monitors where we were able to adjust the monitor brightness, we crossed monitor brightness with software brightness.

In this report, we focus on the colors used on STARS and CARTS (see Tables 1 and 2; refer to Appendix B for a table containing the complete set of tested colors). The measurements for all of the tested colors are available upon request. After the first round of testing, we found that certain colors did not meet the standards. We also had not measured some STARS and CARTS colors that were important for our evaluation. Therefore, in a second round of testing, we tested one additional STARS color, four additional CARTS colors, and four different reds and whites. Because the Yellow for Special Use Airspace (SUA) is displayed typically at a much lower brightness setting, we also measured Yellow at 30% software brightness (see Table 2 for the RGB values for all tested colors at all levels of software brightness).

[2] Note that the colors we refer to as CARTS colors were drawn from the CARTS ACD palette and the colors we refer to as STARS colors were drawn from the STARS TCW palette.

Table 2. RGB Values for the Tested Colors at 100%, 60%, and 30% Software Brightness

	Standard Colors	CARTS Colors	STARS Colors		Other Colors
100% Software Brightness	Black 0,0,0	Green 4 0,139,0	Search Target Blue 30,120,255	History Blue 5 30,30,90	Test Red 1 255,60,60
	White 255,255,255	Deep Sky Blue 0,191,255	History Blue 1 30,80,200	TPA Blue 30,20,255	Test Red 2 255,60,30
	Red 255,0,0	Brown 172,90,0	History Blue 2 70,70,170	Dim Gray 140,140,140	Test Red 3 255,30,60
	Green 0,255,0	Reddish Brown 240,48,0	History Blue 3 50,50,130	Dark Gray Blue 57,115, 115	Test Red 4 255,30,30
	Blue 0,0,255	Gray 38 97,97,97	History Blue 4 40,40,110	Dark Mustard 124,124,64	Test White 1 (on black) 225,225,225
	Yellow 255,255,0				Test White 2 (on black) 215,215,215
					Orange 255,165,0
60% Software Brightness	Black 0,0,0	Green 4 0,83,0	Search Target Blue 18,72,153	History Blue 5 18, 18,54	Test Red 1 153,36,36
	White 153,153,153	Deep Sky Blue 0,115,153	History Blue 1 18, 48,120	TPA Blue 18,12,153	Test Red 2 153,36,18
	Red 153,0,0	Brown 103,54,0	History Blue 2 42,42,102	Dim Gray 84,84,84	Test Red 3 153,18,36
	Green 0,153,0	Reddish Brown 122,29,0	History Blue 3 30,30,78	Dark Gray Blue 34, 69, 69	Test Red 4 153,18,18
	Blue 0,0,153	Gray 38 58,58,58	History Blue 4 24,24,66	Dark Mustard 74,74,38	Test White 1 (on black) 135,135,135
	Yellow 153,153,0				Test White 2 (on black) 129,129,129
					Orange 153,99,0
30% Software Brightness	Yellow (30%) 76,76,0				

For our measurements, we created a set of PowerPoint slides of uniform color that, when displayed, filled the monitor screen. The only two areas on the slide that did not contain the to-be-measured color were a gray rectangle that noted the color name and corresponding RGB values in black text and a black square that noted the slide number in white text (see Figure 4). We performed all measurements in a dark room. To evaluate color consistency across the display, we took measurements in both the center and lower left corner of the monitor. To help focus the spectraphotometer when taking measurements on each monitor, we created a focusing slide that marked the to-be-measured center and corner positions with an X. By using a focusing slide to position the spectraphotometer, we ensured that we captured all center and corner measurements in the same relative locations on all monitors. For our measurements of the first set of colors on the Syncmaster and Flexscan monitors and our measurements of the second set of colors on all monitors, we placed the end of the lens housing 24 inches from the monitor screen.

Figure 4. Sample test slide.

We measured the two COTS displays and the General Digital TDW display at two levels of hardware brightness and two levels of software brightness. We were unable to change the hardware brightness for the Barco 2K, so we measured it only at the two levels of software brightness.

3. RESULTS

We evaluated whether colors used on current terminal systems for attention, identification, or segmentation met their corresponding requirements. We also evaluated text legibility for the selected colors to determine whether all currently used text colors passed the text legibility requirement. We then list selected colors and palettes, described in terms of color names (e.g., Red), CIE color coordinates, and corresponding RGB values on the major terminal displays. When we identified problems with currently used colors, we suggest alternative colors for display elements based on our testing, existing guidelines, and human factors best practices. When alternative colors were required, we selected colors that provided the best performance.

3.1 Attention

The two colors that STARS and CARTS use for attention include Red,[3] which both systems use for alerts, and Yellow, which both systems use to indicate pointouts. Both Red and Yellow have luminance issues related to their use as attentional colors. Appendix C (Tables C2, C3, and C4) contain the results of our attention tests and indicate which color combinations passed the requirements on which monitors and for which settings. The check marks (✓) indicate that a color combination passed the requirements and blank cells indicate that a color combination failed the requirements. A dash (–) indicates that a color was not tested for that combination of monitor software and hardware brightness settings. To read the tables holistically, many check marks indicate good performance and many blank squares indicate poor performance.

On most monitors, at most settings, Red (alerts) did not meet the attentional requirements of either a luminance difference greater than 20 cd/m^2 or a chromaticity difference greater than .24 in CIE coordinates (see Appendix C, Table C2). This was true for Red used on top of the weather colors (Dark Gray Blue, Dark Mustard, Dark Gray [Gray 38], Brown, and Reddish Brown) and Red used on top of the SUA colors (Yellow [30%] and Yellow). Additionally, because Red is always less luminant than White, Green, and Yellow, alerted datablocks also failed to meet the attentional requirements against owned datablocks (White), unowned datablocks (Green), and pointouts (Yellow) on all monitors at all settings. Red generally met the attentional requirements against the display background color (Black), except at the 60% software brightness setting on the Barco monitor and at the 60% hardware/60% software brightness setting on the Flexscan monitor.

On all monitors at all settings, Yellow (pointouts) met the attentional requirement against all weather colors, against the display background color, and against special use airspace (see Appendix C, Table C2). Yellow also met the attentional requirements against unowned datablocks, except at the 60% software brightness setting on the Barco monitor and at the 60% hardware/60% software brightness setting on the Flexscan monitor. In general, Yellow is always less luminant than White. Therefore, it failed to meet the attentional requirement against owned datablocks.

After identifying a problem with Red meeting the attention and text legibility requirements (see section 3.4), we tested variations that might be more luminant than the original Red. We came up with four variants of reds (Test Red 1, 2, 3, and 4), and we tested them for compliance with the requirements (see Appendix C, Table C3). For the attention requirements, the four variants of red performed slightly better than the original Red. An improvement in contrast against the weather colors on the TDW and Flexscan was responsible for most of the differences in performance. This improvement occurred primarily at the 100% hardware/100% software setting and the 100% hardware/60% software setting on the TDW and the 100% hardware/100% software setting and the 60% hardware/100% software setting on the Flexscan. Therefore, we chose Test Red 1 as a replacement for Red.

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[3] We capitalized the color names for tested colors to make a clear distinction between references to tested colors and references to colors in general.

Although Test Red 1 does not pass on all background and contrast colors, it is the most luminant of all the tested reds and provides both an increase in attention performance and an increase in text legibility (see section 3.4) when compared to the original Red. Red also is a good attentional color because it has a standard meaning (see section 4 for a more in depth discussion of this issue). We based the final recommended CIE values for the weather colors on those obtained from the TDW and Flexscan because those were the only weather colors for which Test Red 1 passed the attentional requirements. However, to achieve the recommended CIE coordinates you would need to adjust the RGB values for the weather colors on both the Barco and Syncmaster.

We also found several human factors problems related to using Yellow with White and using Red with White. By definition, pure white (255, 255, 255) is more luminant than any other color on the display, but the attention requirements dictate that Red and Yellow be more luminant than White. To identify a more optimal white, we selected two variants of white (Test White1 and 2) that were somewhat less luminant than the original White and tested them for compliance with the requirements.

Yellow did pass the attentional requirements on many of the monitors against Test White 1 and Test White 2 (see Appendix C, Table C4). As a result of these findings, the identification findings (see section 3.2), and the text legibility findings (see section 3.4), we recommend replacing White with Test White 1. This is a slightly less luminant color that looks somewhat grayish compared to pure white but looks white when placed against a black background. Because we only tested colors at 100% and 60% brightness settings, without further testing we cannot determine whether these colors would pass at lower brightness settings. Therefore, as a caveat, we also recommend that user-selectable brightness controls prevent the adjustment of datablocks (Test Red 1, Yellow, Test White 1, and Green) below 60% brightness.

3.2 Identification

The colors that controllers need to identify on STARS and CARTS include the datablock colors not used for attention (i.e., Green and Test White 1; see section 3.1), the ghost target color (Yellow), the search target and beacon colors (Search Target Blue and Green on STARS and Deep Sky Blue and Green 4 on CARTS), and the weather colors (Dark Mustard and Dark Gray Blue on STARS and Dark Gray [Gray 38], Brown, and Reddish Brown on CARTS). We did not test those datablock colors that are used for attention for compliance with the identification requirements. By definition, colors cannot simultaneously meet the attention requirement of a luminance difference greater than 20 cd/m^2 and the identification requirement of an absolute luminance difference less than 20 cd/m^2. Because Yellow is primarily an attention color, we did not test the ghost target Yellow for compliance with the identification requirement. Instead, we tested Orange to evaluate whether it would be a suitable substitute candidate for use as the ghost target color (see Appendix C, Table C5, for a complete list of colors tested for compliance with the identification requirements).

Because the datablock colors (Test White 1 and Green) and the proposed ghost target color (Orange) are basic colors, they do not need to meet the chromaticity requirement for identification. The STARS and CARTS weather colors, as well as the primary and secondary targets, are nonbasic colors and, therefore, need to meet *both* the chromaticity and the luminance requirements.

All nonbasic color pairs met the chromaticity requirement for all monitors at all brightness settings (as noted in Appendix C, Table C4). However, at many hardware and software brightness settings, on all or most monitors, pairs that failed to meet the luminance requirement included Test White 1 and Green, Search Target Blue and Green, Deep Sky Blue and Green, Test White 1 and Orange, and Green and Orange.

The purpose of the luminance difference requirement is to ensure that one display element used for identification is not more salient (i.e., prominent) than another display element. However, even display elements used for identification do not always have equal importance or "task relevance." If display elements do not have equal task relevance, we believe the element with the higher task relevance should be the element with the higher luminance. Therefore, when elements failed the luminance difference requirement, we performed a second-tier test to determine whether the luminance difference was in the appropriate direction: Do the display elements have unequal task relevance and, if so, was the element with the higher task relevance more luminant than the element with the lower task relevance? If colors met the requirements of this second-tier test of a luminance difference in the appropriate direction, then we deemed it acceptable for use on terminal displays.

For owned (Test White 1) and unowned (Green) datablocks, the owned datablocks should be more luminant than the unowned. We found that for all monitors at all hardware and software brightness settings, the luminance difference for owned and unowned datablocks was in the correct direction. For ghost targets (Orange) and owned datablocks (Test White 1), the owned datablocks should be more luminant than ghost targets. In all cases, the owned datablocks were more luminant than the proposed ghost target color and so met the second-tier requirement. For the ghost targets and the unowned datablocks (Green), either the ghost targets and unowned datablocks should have a difference of less than 20 cd/m^2 or the ghost targets should be more luminant than the unowned datablocks. In no case was the proposed ghost target color more luminant than unowned datablocks. However, on the Barco, the luminance difference was less than 20 cd/m^2 and so it met the luminance difference requirement. Therefore, we recommend using only the CIE values from the Barco for both the Orange proposed for ghost targets and the Green used for unowned datablocks.

To ensure that Orange on the TDW meets the luminance difference requirement for identification, we would need to increase its luminance so that it was no more than 20 cd/m^2 less than the luminance of Green. However, if we increased the luminance of Orange it would become more Yellow. The primary purpose of choosing Orange for ghost targets was to differentiate them from Yellow pointouts. In this instance, we believe that it is more important to meet the chromaticity requirement than to meet the luminance difference requirement.

For search targets and beacon colors on STARS, the luminance difference was not in the correct direction on any monitor at any hardware or software brightness setting. However, the CARTS search target and beacon colors were in the correct direction on all monitors at all hardware and software brightness settings. Therefore, we recommend using the CARTS search target and beacon colors on both STARS and CARTS. We believe that STARS controllers would view this change as relatively minor because the STARS Search Target Blue and CARTS Deep Sky Blue are similar in appearance.

The STARS and CARTS weather colors met the chromaticity requirement on all monitors at all tested brightness settings. Both the STARS and CARTS weather colors met the luminance difference requirements on all monitors at most hardware and software brightness combinations. For those weather color combinations that did not meet the requirements (Dark Gray [Gray 38] and Brown, Dark Gray [Gray 38] and Reddish Brown, Dark Mustard and Dark Gray Blue), they failed only at some settings on the TDW, Syncmaster, and Flexscan, but did not fail at all on the Barco monitor (see Appendix C, Table C3). In cases where the weather colors failed the luminance difference requirement, we evaluated whether the colors indicating more severe weather (Brown and Reddish Brown on CARTS and Dark Mustard on STARS) were more luminant and therefore more salient than the less severe weather colors (Dark Gray [Gray 38] on CARTS and Dark Gray Blue on STARS). In all cases, the luminance differences were in the correct direction, with the more severe weather colors being more luminant and therefore more attention getting than the less severe weather colors.

3.3 Segmentation

For segmentation, we evaluated display elements that used color to differentiate one region or object from another. That is, segmentation is being able to tell where one region or object begins and ends. We tested whether the map lines, range rings, range bearing lines, Predicted Track Line (PTL), MinSep line, buttons, toolbars, J-rings, and J-cones were appropriately segmented from the background and weather. In addition, we evaluated segmentation in the following additional cases.

- When two elements were always displayed in conjunction with one another, we tested whether the first object was appropriately segmented from the second. For example, the PTL extends from the center of the primary target in the current direction of flight. It is important for controllers to be able to tell where the PTL begins and ends. Therefore, we evaluated the segmentation of the PTL color against the background, weather, and target colors.
- We evaluated whether the display appropriately segmented history trails from their nearest neighbor, the primary target, weather, and the background. We also evaluated whether recent history trails were more luminous than older trails.
- We examined how the display segmented weather colors and evaluated whether a person could distinguish different weather levels from each other and from the background.

All of the colors on all of the monitors met either the appropriate chromaticity requirement or the appropriate luminance ratio requirement for regional segmentation. Only two color pairs did not meet the chromaticity requirement or the luminance ratio requirement for pattern segmentation. One pair that did not pass for pattern segmentation was Search Target Blue and History Trail 1. This pair did not pass on the TDW at 100% hardware/60% software brightness or at 60% hardware/60% software brightness. The second pair that did not pass for pattern segmentation was White and Yellow (30%) on the Barco at 60% software brightness. However, because these pairs passed at the 100% hardware/100% software brightness settings, we still used them to calculate the recommended CIE values.

After evaluating the colors against the luminance ratio and chromaticity difference requirements, we evaluated them to see whether they met the luminance difference requirement. In Appendix C, Tables C6 through C13, the check marks (✓) indicate color pairs that passed all requirements, including the luminance difference requirement, for both pattern and regional segmentation. We placed an asterisk (*) next to a check (✓) to indicate the few pairs that did not pass the luminance ratio or chromaticity difference requirements for pattern segmentation. Yellow 30% (Geographic restrictions) met the requirement against both the background and weather at most brightness settings (see Appendix C, Table C6), but Yellow did not. Therefore, we recommend that user-selectable brightness controls prevent the adjustment of the yellow used for Geographic restrictions above 30% brightness.

As with identification, there were many color pairs that did not meet the luminance difference requirement. All those pairs would fail to meet the segmentation requirements, even though the majority passed the chromaticity or luminance ratio requirement. We questioned whether it was reasonable to fail so many colors for having a luminance difference greater than 20 cd/m^2.

The primary purpose of the luminance difference requirement is to ensure that certain display elements are not more visually salient or prominent than other display elements, especially when the display does not use those elements for attention. However, as we stated previously, display elements do not always have equal importance or task relevance. Therefore, we believe it permissible for display elements with unequal importance *not* to meet the luminance difference requirement. For instance, not all datablocks are equally important or *task relevant* to the controller. Generally, owned datablocks have more task relevance than unowned datablocks. History Trail 1 is more task relevant than History Trail 2. Additionally, if the display or some display elements are highly luminant, then there could be problems meeting both the luminance ratio and the luminance difference requirement for pattern segmentation. If a display element has a luminance of 100 cd/m^2 or higher and is used for pattern segmentation, it cannot, by definition have both a luminance ratio greater than 20% and a luminance difference less than 20 cd/m^2.

Because of the great number of color pairs that failed the luminance difference requirement for segmentation and issues related to simultaneously meeting the luminance ratio and luminance difference requirements, we reevaluated color pairs that failed to meet the luminance difference requirement. We assessed them against the same second-tier requirement we used to evaluate colors that failed the luminance difference requirement for identification, and we determined whether the more task-relevant display element was more luminant than the less task-relevant display element.

We examined the weather colors and found that, even in cases where the luminance difference was greater than 20 cd/m^2, the luminance difference was in the appropriate direction. The more severe weather color was always more luminant than the less severe weather color, and weather was always more luminant than the background (see Appendix C, Table C7).

For map lines, Dim Gray (Gray 56), and range rings, Dim Gray (Gray 56), and Dark Gray (Gray 38), we found that the luminance difference for Dim Gray (Gray56) was always in the appropriate direction (i.e., more luminant) when tested against the background and weather (see Appendix C, Table C8). However, Dark Gray (Gray 38) was less luminant than many of the weather colors. This makes sense because Dark Gray (Gray 38) is the weather color for level 1 and 2 on CARTS, and so, by definition, should be less luminant than the weather 3-6 colors. Therefore, we recommend using Dim Gray (Gray 56) for map lines and range rings on both STARS and CARTS.

The PTL and MinSep line were always more luminant than – and therefore appropriately segmented from – the background and weather (see Appendix C, Table C9). We also evaluated whether the displays appropriately segmented the PTL and MinSep lines from target colors. Even though targets are important display elements, we think that the MinSep line is more relevant to the controller when they activate it. Therefore, it should be more luminant than the target. Although the PTL is not as operationally important as targets, terminal controllers typically activate it briefly. During its activation, the controllers need to attend to it quickly. Only in that brief instance is the PTL more salient. Because White by definition is always more luminant than other colors, the luminance differences for both the MinSep line and PTL were in the correct direction.

We examined primary targets and found that displays appropriately segmented both CARTS and STARS primary targets from the background and from weather (see Appendix C, Table C10). As noted for identification, the STARS Search Target Blue was not more luminant than the STARS beacon, but the CARTS target color (Deep Sky Blue) was more luminant than the CARTS beacon (Green 4). As before, we recommend that STARS adopt CARTS colors for beacons and targets.

We found that the displays appropriately segmented all of the history trails from their nearest neighbor (see Appendix C, Table C11). Trails that were more recent were more luminant than older trails. We also found the displays appropriately segmented all history trails from the primary target (Search Target Blue and Deep Sky Blue) and the background. For cases where the history trails did not pass the luminance difference requirement, the luminance of the history trails was less than the luminance of the weather. At a 100% brightness setting, History Trail 1 and History Trail 2 were the only two colors that passed the luminance difference requirement, and they passed only on the Barco. Therefore, we used the CIE values for the Barco at 100% to determine the recommended x y color coordinates for the history trails. We also recommend tying the brightness setting of the history trails directly to the brightness of the primary target. That is, the system should prevent controllers from adjusting the history trail brightness so that the history trail is brighter than the primary target. We were unable to obtain the RGB values for the history trails on CARTS, so we were unable to test them for compliance with this requirement.

There is also a known issue for history trails when layered on top of weather. If the weather brightness controls are set unusually high (i.e., 100% brightness) and older history trails are placed on top of weather, an optical illusion occurs. This illusion causes the older history trails to appear as holes in the weather. In the field, during normal use, the controllers typically turn down the brightness of the weather and do not encounter this effect. Given this known issue and the fact that the older history trails did not meet segmentation requirements on weather at 100% brightness, we recommend that user-selectable brightness controls prevent the adjustment of weather colors (Dark Gray Blue, Dark Mustard, Dark Gray [Gray38], Brown, and Reddish Brown) above 60% brightness.

We found that Yellow highlights were less luminant than the White text used for the mouseover text in toolbars (see Appendix C, Table C12). Although it might make sense to highlight this toolbar text by making it brighter, the text is White. White is already the brightest color on the display, so designers cannot make it any brighter. However, because yellow is used for attentional purposes in a tactical context, it may also be used as an attention-getting or highlighting device in a nontactical context. In fact, yellow highlighters are often used to highlight text in books. For these reasons, we believe that the use of yellow in this context conforms to standard usage. Therefore, we do not recommend making any changes to either the highlights or the text.

The system status area uses Cyan to indicate weather items and Green to indicate nonweather items. We found that Cyan was more luminant than Green (see Appendix C, Table C12). Because controllers, as a job requirement, must be able to determine which weather levels are coming into the system and which are being displayed on the workstation, weather has more task relevance than nonweather. Therefore, it is appropriate for Cyan to be more luminant than Green.

For cases where J-rings and J-cones (TPA Blue) did not pass the luminance difference requirement, some were in the appropriate direction and some were not (see Appendix C, Table C13). Although the luminance of the J-rings and J-cones was less than the luminance of range bearing line, MinSep line, and PTL, we believe that the purposes served by the lines are more critical than the purposes served by J-rings and J-cones. Therefore, those luminance differences were in the appropriate direction. However, the luminance of the J-rings and J-cones was less than the luminance of the weather, which is not in the appropriate direction. At a 100% brightness setting, the J-rings and J-cones only passed the luminance difference requirement on the Barco. Therefore, we used the CIE values for the Barco at 100% brightness to determine the recommended (x) and (y) color coordinates for the J-rings and J-cones.

3.4 Text Legibility

We evaluated whether text colors passed the requirement for text legibility (HF-STD-002, 3.3.1). For this requirement, the Michelson contrast (see Equation 8) between the text and background must be greater than 30%. On STARS and CARTS, most of the text is White, Green, Yellow, or Red, which are the colors used for datablocks. This text can appear against the background, weather colors, or SUA. Text also appears on buttons, menus, toolbars, and lists.

On all monitors at all brightness level settings, all text colors except Red passed the text legibility requirement against most STARS and CARTS background colors. However, they did not pass the text legibility requirement against SUA Yellow (see Appendix C, Table C14). Therefore, we again recommend using Yellow at 30% brightness for SUA; that is, the controllers should not be able to adjust the brightness higher than 30% for SUA Yellow.

Although the Red text against the display background (Black) performed well on most monitors, it did not pass at 60% brightness on the Barco monitor currently in use in en route. This could be a potentially serious problem if the FAA ever deploys Barco displays to terminal controllers and maintains the same Red. On terminal displays, text appears against a Black background more frequently than it appears against other backgrounds, such as the weather background. There are also problems with the legibility of Red text against the weather background colors at many combinations of hardware and software brightness settings. This is especially true for the weather background colors used to depict the most severe weather levels (Dark Mustard and Reddish Brown).

We evaluated Test Red 1-4, Test White 1 and 2, and Orange as potential alternatives to the currently used text colors. Test Red 1 performed the best of all the test reds (see Appendix C, Table C15). Given this outcome, the problems with Red meeting text legibility requirements, and the previous findings for attention, we recommend using Test Red 1 in place of the currently used Red. We also recommend using Test White 1, because Test White 1 and 2 performed equally as well as White in terms of legibility, but performed better than White for both attention and identification.

We did find some problems with the legibility of Green 4, which is the CARTS color used for lists and list titles. The use of Green 4 on weather colors caused most of the problems, but there were also some issues with its use on Black. Because Green performed well in terms of text legibility, and because STARS currently uses Green for lists and list titles, our recommendation is to use Green for lists and list titles on both STARS and on CARTS. This would not only eliminate the problem on CARTS, but would also make the color palettes on the two systems more consistent. This should be a minor change for controllers because Green 4 on CARTS and conventional Green on STARS have a similar appearance. Orange, the color we propose for ghost targets, passed the text legibility requirement against STARS and CARTS background colors on all monitors at all brightness level setting except against SUA yellow.

4. RECOMMENDATIONS

Summarizing our findings, we still recommend using Black for the background color, Yellow for pointouts, TPA Blue for J-rings and J-cones, History Trail 1-5 for history trails, and Cyan for weather in lists on both STARS and CARTS. However, we do not recommend making any changes to the weather colors on CARTS or any changes to the weather colors on STARS even though they are not currently consistent. We are aware that there is a separate effort underway to develop a standardized color set for weather colors, and we believe that this effort will produce a single color palette for both displays. Also, we believe that the R-ACD Systems and the STARS TDWs used in towers should also be brought into conformance with the color palette used in the TRACON on both the STARS TCW and the CARTS ACD.

We did find that a number of current terminal automation system colors required changes. Therefore, we recommend making the following changes. First, we recommend changing the current Red to Test Red 1. Test Red 1 is more luminant than the currently used red. Test Red 1 also performs better than Red against both the STARS and CARTS weather colors for attention. Test Red 1 represents the best red that we tested and it represents an improvement over the red currently used by STARS and CARTS. It represents a compromise between brightness and redness. However, we also believe that red may warrant additional research.

The identification results indicated that the CARTS search target and beacon colors (Deep Sky Blue and Green 4) met the requirements, but the STARS search target and beacon colors (Search Target Blue and Green) did not meet the requirements. Given these findings, we recommend using the CARTS search target and beacon colors for both CARTS and STARS. On the basis of the text legibility results, we recommend using Green 4 for the Range Bearing Line, List Titles, Previews, System Status, Coordination Rundown lists, and beacons, and we recommend using Green for datablocks on both STARS and CARTS. Because the displays currently use Yellow for pointouts, we recommend using Orange for ghost targets, instead of Yellow. Additionally, we recommend using Test White 1 for datablock text because it is as legible as White but performed better in terms of both attention and identification. We recommend using Dim Gray (Gray 56) for the compass rose, map lines, and range rings on both STARS and CARTS. Lastly, given the text legibility results, we recommend using Yellow 30% for SUA.

Table 3 contains our final list of recommended colors for terminal automation systems. The table contains the major elements of an ATC situation display and provides recommended values in the CIE color space for each element. The table lists the color's function, the color name, the recommended luminance value for TRACON and tower environments, the range of acceptable x and y CIE coordinates, and the RGB value that we found produced those CIE values on our sRGB monitors. To account for measurement error, we used a tolerance in the range ± 5 cd/m^2 for luminance, and a value of ± .01 for chromaticity xy coordinates. These tolerances correspond to the acceptable range of values seen across measurements made on the different monitors.

We list CIE coordinates for all of the colors. However, in addition to the CIE coordinates, we also provide corresponding RGB values tested on several COTS monitors. The expectation is that application designers should only use the provided RGBs as a starting point. However, the RGB values, used on a specific display, may fail to produce the required CIE values. In this case, application designers should adjust the RGBs incrementally until they produce the appropriate CIE values. If an application fails to meet the CIE requirements on one display, application designers will need to select a different display. Application designers should not need to adjust the RGB values as much when using an appropriately calibrated and sRGB compliant display.

For referent colors, which are colors that you refer to when adjusting the luminance of nonreferent colors, the table lists the recommended luminance ranges for TRACON environments and the recommended luminance for the tower environment. For nonreferent colors, the table lists the ratio of the nonreferent luminance to the referent luminance. If a color is a referent color, it is indicated as such in the Luminance Referent column.

Table 3. Recommended Colors and Corresponding CIE and RGB Values

Function	Color	L cd/m^2 (TRACON environment)	L cd/m^2 (Tower Environment)	Luminance Referent	Ratio of Nonreferent Luminance to Referent Luminance	x	y	RGB Value Starting Point
Background	Black			Test white 1	.2%	.26-.34	.28-.31	0,0,0
Owned Datablocks, PTL, MinSep	Test White 1	135.05-383.75	472.30-482.30	**Referent**	100%	.31-36	.33-.37	225,225,225
Limited/Partial/ Unowned Datablocks,	Green	95.12-105.12	391.25-401.25	**Referent**	100%	.31-.33	.54-.56	0,255,0
Alert Datablock (all types)	Test Red 1	93.88-103.88	153.80-163.80	**Referent**	100%	.61-.62	.33-.35	255,60,60
Pointout Identifier/ SA/MI	Yellow	347.90-357.90	505.55-515.55	**Referent**	100%	.41-.42	.50-.51	255,255,0
Ghost Target	Orange	76.00-85.00	285.45-295.45	**Referent**	100%	.47-.49	.43-.45	255,165,0
Search Target Symbol	Deep Sky Blue			Cyan	67%	.19-.23	.23-.34	0,191,255
Beacon Target Extent Range Bearing Line, List Titles, Preview, System Status, Coordination Rundown	Green 4			Green	30%	.29-.32	.55-.60	0,139,0
History Trail 1	Blue	19.83-29.83	84.44-94.44	**Referent**	100%	.17-.19	.17-.19	30,80,200
History Trail 2	Blue			History Trail 1	78%	.20-.22	.19-.21	70,70,170
History Trail 3	Blue			History Trail 1	38%	.19-.21	.18-.20	50,50,130
History Trail 4	Blue			History Trail 1	25%	.18-.20	.17-.19	40,40,110
History Trail 5	Blue			History Trail 1	15%	.18-.20	.17-.19	30,30,90
Compass Rose/Maps A & B/Range Rings	Dim Gray (Gray 56)			Test White 1	35%	.29-.32	.32-.34	140,140,140
Weather 1, 2, 3	Dark Gray Blue			Cyan	17%	.23-.24	.33-.34	57,115,115
Weather 1,2/Range Rings	Dark Gray			Test White 1	13%	.29-.32	.33-.34	96,96,96
Weather 3, 4	Brown			Red	66%	.56-.57	.38-.39	172,90,0
Weather 4, 5, 6	Dark Mustard			Yellow	20%	.37-.39	.45-.47	124,124,64
Weather 5, 6	Reddish Brown			Red	66%	.62-.63	.34-.35	204,48,0
TPA (J-rings and cones)	TPA Blue			History Trail 1	88%	.15-.17	.13-.15	30, 20,255
Geographic restriction	Yellow (30%)			Yellow	7%	.41-.44	.45-.49	76,76,0
Weather in lists	Cyan	122.3-300.80	465.50-475.50	**Referent**	100%	.21-.23	.32-.34	0,255,255

Once a display designer selects a luminance for the referent from the range of values provided in the table, they can adjust nonreferent luminances, relative to the referent, using the given luminance ratio. For example, if a designer selects Green, which is a referent color, for use in the TRACON environment, the designer may select a luminance value ranging from 95.12 to 105.12 cd/m^2. If a designer selects Green 4, which is not a referent color, for use in the TRACON environment, the designer must first select a luminance for its given referent color (Green). After selecting the luminance for Green using a value ranging from 95.12 to 105.12 cd/m^2, the designer would adjust the luminance of Green 4 to 30% of the luminance selected for Green. However, note that linked referent and nonreferent colors do not necessarily share the same brightness controls on the controller's console.

We selected these colors to provide a color palette with the best human factors attributes for the main controller situation displays in both the approach control and tower environments. We selected each color based on how well it conformed to human factors standards and best practices, how well it performed in combination with other colors, and how well it matched existing controller training and operational experience. Human factors and operational Subject Matter Experts should evaluate the appropriateness of these recommendations for other applications or environments prior to any implementation.

We recommend that user-selectable brightness controls for datablocks be locked to prevent the controllers from lowering the brightness below 60%. We recommend that the system couple the brightness setting of the history trails with the brightness of the primary target so that controllers cannot set the history trail brightness to be greater than that of the primary target. Even though displays currently provide the capability to display SUA using Yellow at 100% brightness, on the basis of the text legibility results, we recommend using Yellow 30% (i.e., Yellow at 30% brightness) for this display feature. To maintain the effectiveness of weather features on the display, the display should not allow the brightness settings of weather elements to be adjusted above 60%.

There are a number of issues encountered during this study that application designers should consider when selecting an appropriate color palette. Of primary concern is the use of red for attention. White, green, and yellow are always more luminant than red. However, the requirements necessitate that red be more luminant than other display elements if being used for attention. Because the conventional meaning for red is "alert" and one of the guidelines states that color use shall always be consistent with its standard meaning (HF-STD-002, 3.3.5), we have a conundrum. How do we fix red to meet both these requirements? The answer is that we do not need to fix red any more than we have already done. Research demonstrates that people are much quicker to respond to red and yellow than they are to other colors (Ochiai & Sato, 2003). In addition, because red is the universal color for alerts, it would not make sense to substitute another color for red. Although we have tried to bring the luminance of red and white closer together, red will never be more luminant than white.

A second issue relates to identifying a white that meets both the legibility requirements and the identification requirements, without appearing too luminant against red. To decrease the luminance difference between red and white, we reduced the brightness of white, which gave us Test White 1. We also increased the luminance of red, which gave us Test Red 1. However, there are inherent problems with reducing the brightness of white. Less bright white is gray. At slight brightness reductions, a grayish white against a black background still appears to be white, but as the size of a display element increases, its "grayness" becomes more noticeable. Test White 1 still appears to be white when used for display elements, such as text or lines. However, large display elements (e.g., large, filled-in shapes) should not use Test White 1 because its "grayness" would become more obvious.

There were other luminance issues related to colors being used for both attention and identification or attention and segmentation. As we pointed out, a pair of colors cannot simultaneously meet both the *attention and identification* or the *attention and segmentation* luminance difference requirements. Therefore, it is important that application designers not use any color simultaneously for attention and identification or attention and segmentation. If a color is being used for attention, it should not also be used for segmentation or identification. If it becomes necessary to use a color for both attention and identification or attention and segmentation, the attention requirements should take precedence over other requirements. If a color is being used for *identification* and *segmentation* and the requirements conflict, then meeting the identification requirement should take precedence over meeting the segmentation requirement. If a color is being used for text and either identification or segmentation, the legibility requirement should take precedence over any other requirements.

Another issue of concern is the great number of display elements used for identification and segmentation that failed to meet the luminance difference requirement. Because of this and because display elements sometimes cannot meet both the luminance ratio and luminance difference requirements for pattern segmentation, we believe the luminance difference requirements for identification (HF-STD-002, 3.2.2.4) and segmentation (HF-STD-002, 3.2.3.2) should be modified to be *should's* rather than *shall's*. The only instance when a *shall* would be appropriate would be for the case where display elements were truly of equivalent salience. For instance, if a new ATC display were to color code altitudes, one altitude would not be more important than another altitude. In that instance, it would be appropriate for all of the colors to be equally luminant. However, in many cases when displays use color for identification or segmentation, one element has more task relevance than another. For example, search targets have more task relevance for air traffic controllers than beacons. Even though the color of search targets is not used for attention in the way red is used to draw attention to alerts, search targets should draw more attention than beacons. If colors used for identification or segmentation fail to meet the luminance difference requirement, but one display element has more task relevance than another display element, the evaluator should examine whether the luminance difference is in the appropriate direction and the more task-relevant display element is more luminant than the less task-relevant display element. Additionally, for those colors that have characteristic meanings, we believe it is more important to conform to any conventional meaning than to defy convention simply to meet a luminance requirement.

We developed this color standard with the assumption that someone will calibrate monitors appropriately in the field. Therefore, we recommend that, along with the implementation of the color standard, there be a requirement for Technical Operations personnel to calibrate monitors on a regular schedule. We also recommend providing only limited options for adjusting the brightness of monitors. The purpose of developing a color standard is to determine colors that provide optimal benefits for the controllers in terms of information transfer and human performance. However, we developed the standard using colors tested at specific brightnesses.

If the monitors can be adjusted through 100 steps of brightness and the brightnesses of different display elements can be adjusted individually, then we allow for the possibility of color combinations that do not meet these requirements. By minimizing the capability to adjust brightness to only a few settings (e.g., high, medium, and low) and by linking the brightness adjustments of certain display elements, we avoid the use of nonoptimal color combinations. In addition, we assure that the controllers gain the most in terms of performance benefits, and we make it easier for researchers to perform the appropriate measurements when adding new colors to a display.

We realize that there may be workforce issues related to setting a limitation on the number of brightness settings. However, there is a great deal of human factors literature that demonstrates the dangers of allowing too many degrees of freedom in control settings. The greater the number of degrees of freedom, the more chances there are for errors.

5. CONCLUSIONS AND FUTURE RESEARCH

Future studies should evaluate *which* and *how many* brightness settings we should allow on the controller display. Future research should also examine the issues related to the color coding of ownership to determine whether the color coding of ownership provides operational benefits or costs. In future research, we may also want to more systematically map sRGB colors to CIE values. In theory, with such a mapping, we could determine more precisely which sRGB values produce the required CIE values. Future work should also continue to focus on identifying ATC information for which color coding could provide operational benefits. Potential operational benefits include improvements to safety, efficiency, or controller workload. The following are examples of ATC information that could be color coded on future terminal ATC situation displays.

- Area Navigation (RNAV) status.
- Automatic Dependent Surveillance–Broadcast (ADS-B) equipage.
- Converging Runway Descent Aid (CRDA) ghost target.
- Arrival runway.
- Arrival, departure, overflight status.
- Arrival airport (Primary/Secondary).
- General aviation, commercial carrier, or military aircraft type.
- Ultra-light, Unmanned Aerial Vehicles (UAVs), prop, turbo prop, jet, heavy, ultra-heavy aircraft type.
- Suspect aircraft.
- Departure fix (A, B, C, or D).
- Destination airport.
- Aircraft direction or intent (climbing, descending, or level).

Because we have measured the CIE values for many colors not discussed in this paper, system developers could easily use the database[4] that we created for selecting colors for new display elements (e.g., ADS-B, RNAV, CRDA, UAVs). For instance, if a display designer wanted to use Purple to indicate ADS-B equipage, they would first determine whether an equipage

[4] This database can be obtained by contacting the researchers.

indicator serves an attention, identification, or segmentation function. If they determined that it served an identification function, they would determine whether the chromaticity difference between Purple and other datablock colors was more than .04 in CIE uniform chromaticity coordinates. They would also check whether the luminance difference between Purple and other datablock colors was less than 20 cd/m^2. If Purple did not meet the luminance difference requirement, they would need to determine the relative importance of ADS-B equipage as compared to other datablock colors. If Purple met the requirements on all monitors at 100% brightness, then system developers would use the CIE values from all four monitors to determine the recommended CIE coordinates. However, if it only met the requirements on one, two, or three monitors at 100% brightness, then they would only use the monitors that met the requirements to determine the recommended CIE coordinates. Because equipage would be in the datablock and could affect text legibility, they would also need to evaluate Purple for compliance with the text legibility requirement.

When determining ATC information for which color coding could provide operational benefits, system designers should be wary about using too many color codes for too many different display elements. When there are too many colors on a display, the “skittles” effect becomes a problem. The skittles effect occurs when the display appears too busy due to the overuse of color and leaves the user with the subjective impression that there are too many colors. This makes it hard for the user of the display to attend selectively to any one color. Color essentially loses its effectiveness for attention, identification, and segmentation purposes.

Although we make recommendations for the current elements that are color coded on today’s terminal displays, we do not comment on the wisdom or value of those color codes. Future research might want to examine whether we should continue to color code currently coded display elements or whether we might gain more from color coding other information. For instance, terminal displays currently color code aircraft ownership. However, research in perception, cognitive psychology, and human factors suggests potential problems with color coding of ownership (Müller et al., 2006; Triesman & Gelade, 1980; Wolfe, 2000). Controllers may learn to attend to information presented in one color and ignore information presented in other colors. This could create potential problems in ATC where a controller must separate owned aircraft not only from each other but also from unowned aircraft and aircraft in other sectors (Cardosi & Hannon, 1999). Although the attention literature suggests there may be issues related to the color coding of ownership, we are neither sure of the extent to which it causes a problem in ATC, nor are we sure if any problem it may cause outweighs its benefits.

The main caveat with our recommended color set is that we created it specifically for terminal ATC situation displays. It reflects the priorities and realities of that specific application and environment. We created the final set of colors using a set of known display elements with known functions. Therefore, the color set meets the requirements given those functions. For example, we selected the blues for the history trails because they needed to appear dimmer than the current target and the current target is a bright blue. Although they meet the constraints put on the design by the standards, the intended operational use, the environment, the technology, and the controllers’ existing practices, they are not necessarily the best colors for all applications or for all environments. Due care should be taken by application designers when selecting color palettes for different operational conditions and systems.

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Acronyms

ACDs	Automated Radar Terminal System Color Displays
ADS-B	Automatic Dependent Surveillance – Broadcast
ATC	Air Traffic Control
CARTS	Common Automated Radar Terminal System
cd/m^2	Candelas per Square Meter
CHI	Computer-Human Interface
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
COTS	Commercial-Off-The-Shelf
CRDA	Converging Runway Descent Aid
CRT	Cathode Ray Tube
DLP	Digital Light Processing
ERP	Engineering Research Psychologist
FAA	Federal Aviation Administration
L	Luminance
LCD	Liquid Crystal Display
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
PTL	Predicted Track Line
R-ACD	Remote ARTS Color Display
RGB	Red, Green, Blue Color Space
RNAV	Area Navigation
sRGB	Standardized Red, Green, Blue Color Space
STARS	Standard Terminal Automation Replacement System
SUA	Special Use Airspace
TCW	Terminal Controller Workstation
TDW	Tower Display Workstation
TRACON	Terminal Radar Approach Control
UAV	Unmanned Aerial Vehicle

Appendix A

Suggested Color Standards and Reference Works

Suggested Color Standards and Reference Works

American Society for Testing and Materials. (2003). *Standard practice for obtaining colorimetric data from a Visual Display Unit using tristimulus colorimeters* (ASTM E1455-03). West Conshohocken, PA: ASTM.

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[5] This will replace the 2001 VESA Flat Panel Display Measurements Standard.

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Appendix B

RGB Values for the Tested Colors

Table. RGB Values for the Tested Colors at 100%, 60%, and 30% Software Brightness

	Standard Colors	CARTS Colors	CARTS Colors 2	STARS Colors	STARS Colors 2	Xing Colors	Other Colors
100% Software Brightness	Black 0,0,0	Gray 38 97,97,97	Green 4 0,139,0	Search Target Blue 30,120,255	TPA Blue 30,20,255	Purple 102,0,153	Test Red 1 255,60,60
	White 255,255,255	Orange 4 139,90,0	Deep Sky Blue 0,191,255	History Blue 1 30,80,200		Xing Brown 153,75,0	Test Red 2 255,60,30
	Red 255,0,0	Orange Red 205,55,0	Brown 172,90,0	History Blue 2 70,70,170		Orange 255,165,0	Test Red 3 255,30,60
	Green 0,255,0		Reddish Brown 240,48,0	History Blue 3 50,50,130		Xing Cyan 0,155,255	Test Red 4 255,30,30
	Blue 0,0,255			History Blue 4 40,40,110		Xing Black 25,25,25	Test White 1 (on black) 225,225,225
	Yellow 255,255,0			History Blue 5 30,30,90		Medium Gray 192,192,192	Test White 2 (on black) 215,215,215
	Cyan 0,255,255			Dim Gray 140,140,140		Yellow Green 153,204,51	Wheat 245,222,179
	Magenta 255,0,255			Dark Gray Blue 57,115,115		Pink 255,192,203	
				Dark Mustard 124,124,64			
60% Software Brightness	Black 0,0,0	Gray 38 58,58,58	Green 4 0,83,0	Search Target Blue 18,72,153	TPA Blue 18,12,153	Purple 61,0,91	Test Red 1 153,36,36
	White 153,153,153	Orange 4 83, 54,0	Deep Sky Blue 0,115,153	History Blue 1 18,48,120		Xing Brown 91,45,0	Test Red 2 153,36,18
	Red 153,0,0	Orange Red 123,33,0	Brown 103,54,0	History Blue 2 42,42,102		Orange 153,99,0	Test Red 3 153,18,36
	Green 0,153,0		Reddish Brown 122,29,0	History Blue 3 30,30,78		Xing Cyan 0,93,153	Test Red 4 153,18,18
	Blue 0,0,153			History Blue 4 24,24,66		Xing Black 15,15,15	Test White 1 (on black) 135,135,135
	Yellow 153,153,0			History Blue 5 18, 18,54		Medium Gray 115,115,115	Test White 2 (on black) 129,129,129
	Cyan 0,153,153			Dim Gray 84,84,84		Yellow Green 91,122,30	Wheat 147,133,107
	Magenta 153,0,153			Dark Gray Blue 34,69,69		Pink 153,115,121	
				Dark Mustard 74,74,38			
30% Software Brightness	Yellow (30%) 76,76,0						

Appendix C

Results of Requirement Tests

Table C1. Coding for monitor types

Code	Monitor Type and Setting
B1	BARCO monitor at 100% software brightness
B2	BARCO monitor at 60% software brightness
T1	TDW monitor at 100% Hardware, 100% software brightness
T2	TDW monitor at 100% Hardware, 60% software brightness
T3	TDW monitor at 60% Hardware, 100% software brightness
T4	TDW monitor at 60% Hardware, 60% software brightness
S1	Syncmaster monitor at 100% Hardware, 100% software brightness
S2	Syncmaster monitor at 100% Hardware, 60% software brightness
S1	Syncmaster monitor at 60% Hardware, 100% software brightness
S2	Syncmaster monitor at 60% Hardware, 60% software brightness
F1	Flexmaster monitor at 100% Hardware, 100% software brightness
F2	Flexmaster monitor at 100% Hardware, 60% software brightness
F3	Flexmaster monitor at 60% Hardware, 100% software brightness
F4	Flexmaster monitor at 60% Hardware, 60% software brightness

Note. Barco = Barco 2K (MDP-471) LCD display; TDW = General Digital (90-850-021-1) LCD display; Sync = Samsung Syncmaster (244T) LCD monitor; and Flex = Eizo Flexscan (S21411W-U) LCD monitor.

Table C2. Testing Red and Yellow for Compliance with the Attentional Requirements

Display Element	System	Color	Background/ Contrast Color	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Datablock Alerts- EM/ System Status Alerts	CARTS and STARS	Red	Black	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
			White	✓													
			Yellow														
			Green														
			Dark Gray Blue											✓		✓	
			Dark Mustard											✓		✓	
			Dark Gray (Gray 38)			✓	✓	✓	✓	✓	✓	✓		✓		✓	
			Brown											✓		✓	
			Reddish Brown											✓		✓	
			Yellow (30%)	–[a]		–		–		–		–		–		–	
Pointouts	CARTS and STARS	Yellow	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			White														
			Green			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
			Dark Gray Blue	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Dark Mustard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Reddish Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Yellow (30%)	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓

[a]Yellow (30%) was only tested at the 60% software settings.

Table C3. Testing Four Variants of Red for Compliance with the Attentional Requirements

Color	Background/ Contrast Color	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Test Red 1	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	White														
	Yellow														
	Green					✓						✓		✓	
	Dark Gray Blue			✓	✓		✓	✓	✓	✓		✓		✓	
	Dark Mustard			✓	✓							✓		✓	
	Dark Gray (Gray 38)	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
	Brown			✓	✓							✓		✓	
	Reddish Brown			✓	✓	✓			✓			✓		✓	
	Yellow (30%)	–		–	✓	–	✓	–		–		–		–	
Test Red 2	Black	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	White														
	Yellow														
	Green														
	Dark Gray Blue			✓	✓		✓	✓				✓		✓	
	Dark Mustard			✓	✓							✓		✓	
	Dark Gray (Gray 38)	✓		✓	✓	✓	✓	✓	✓	✓		✓		✓	
	Brown			✓	✓		✓					✓		✓	
	Reddish Brown			✓	✓	✓						✓		✓	
	Yellow (30%)	–		–	✓	–	✓	–		–		–		–	

(table continues)

Table C3 (continued). Testing Four Variants of Red for Compliance with the Attentional Requirements

Color	Background/ Contrast Color	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
	Black	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	White														
	Yellow														
	Green														
Test Red 3	Dark Gray Blue			✓	✓		✓					✓		✓	
	Dark Mustard			✓	✓							✓		✓	
	Dark Gray (Gray 38)			✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	
	Brown			✓	✓		✓					✓		✓	
	Reddish Brown			✓	✓							✓		✓	
	Yellow (30%)	–		–		–	✓	–		–		–		–	
	Black	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	White														
	Yellow														
	Green														
Test Red 4	Dark Gray Blue			✓	✓		✓					✓		✓	
	Dark Mustard			✓	✓							✓		✓	
	Dark Gray (Gray 38)			✓	✓	✓	✓	✓	✓	✓		✓		✓	
	Brown			✓	✓		✓					✓		✓	
	Reddish Brown			✓	✓							✓		✓	
	Yellow (30%)	–		–		–		–		–		–		–	

Table C4. Testing Two Variants of White for Compliance with the Attentional Requirements

Color	Background/ Contrast Color	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Test White 1	Red														
	Test Red 1														
	Test Red 2														
	Test Red 3														
	Test Red 4														
	Yellow		✓		✓	✓		✓		✓	✓		✓		
Test White 2	Red														
	Test Red 1														
	Test Red 2														
	Test Red 3														
	Test Red 4														
	Yellow			✓	✓	✓	✓		✓		✓	✓	✓	✓	

Table C5. Testing Datablock, Ghost Target, Search Target, Beacon, and Weather Colors for Compliance with the Identification Requirements

Display Element	System	Color Pairs	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Datablocks	CARTS and STARS	White and Green														
		Test White 1 and Green		✓			✓	✓		✓		✓		✓	✓	✓
		Test White 2 and Green		✓		✓		✓		✓		✓	✓	✓	✓	✓
Ghost Targets		White and Orange														
		Test White 1 and Orange														
		Test White 2 and Orange														
		Orange and Green	✓	✓												✓
Search Targets/ Beacons	STARS	Search Target Blue and Green														
	CARTS	Deep Sky Blue and Green 4		✓												
Weather	STARS	Dark Mustard and Dark Gray Blue	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	CARTS	Brown and Dark Gray (Gray 38)	✓	✓		✓	✓	✓		✓		✓		✓	✓	✓
		Brown and Reddish Brown	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Reddish Brown and Dark Gray (Gray 38)	✓	✓		✓	✓	✓		✓		✓		✓	✓	✓

Note. All colors passed the chromaticity requirement. These colors failed only the luminance difference requirement.

Table C6. Testing List Titles, Lists Previews, System Status, the Range Bearing Line, and Geographic Restrictions for Compliance with Segmentation Requirements

Display Element	System	Color 1	Color 2	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
List Titles, Lists, Preview, System Status/Range Bearing Line	STARS	Green	Black														
			Dark Gray Blue														
			Dark Mustard														
			Dark Gray (Gray 38)														
			Brown														
			Reddish Brown														
	CARTS	Green 4	Black		✓				✓						✓		✓
			Dark Gray Blue	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Dark Mustard	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
			Dark Gray (Gray 38)	✓	✓		✓	✓	✓		✓		✓		✓	✓	✓
			Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			Reddish Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Geographic Restriction	STARS and CARTS	Yellow	Black														
			Dark Gray Blue														
			Dark Mustard														
			Dark Gray (Gray 38)														
			Brown														
			Reddish Brown														
		Yellow (30%)	Black	–	✓	–		–	✓	–		–		–	✓	–	✓
			Dark Gray Blue	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓
			Dark Mustard	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓
			Dark Gray (Gray 38)	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓
			Brown	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓
			Reddish Brown	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓

Table C7. Testing Weather for Compliance with Segmentation Requirements

Display Element	System	Color 1	Color 2	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Weather	STARS	Dark Gray Blue	Dark Mustard	✔	✔		✔	✔	✔		✔	✔	✔	✔	✔	✔	✔
			Black		✔				✔						✔		✔
		Dark Mustard	Black		✔										✔		✔
	CARTS	Dark Gray (Gray 38)	Brown	✔	✔		✔	✔	✔		✔		✔		✔	✔	✔
			Reddish Brown	✔	✔		✔	✔	✔		✔		✔		✔	✔	✔
			Black		✔		✔		✔				✔		✔	✔	✔
		Brown	Reddish Brown	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
			Black		✔				✔						✔		✔
		Reddish Brown	Black		✔		✔								✔	✔	✔

Table C8. Testing Map Lines and Range Rings for Compliance with Segmentation Requirements

System	Color 1	Color 2	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
STARS	Dim Gray (Gray 56)	Black		✓										✓		✓
		Dark Gray Blue		✓				✓		✓		✓		✓		✓
		Dark Mustard	✓	✓		✓		✓		✓		✓		✓	✓	✓
		Dark Gray (Gray 38)		✓								✓		✓		✓
		Brown	✓	✓						✓		✓		✓	✓	✓
		Reddish Brown		✓		✓		✓		✓		✓		✓	✓	✓
CARTS	Dark Gray (Gray 38)	Black		✓		✓		✓				✓		✓	✓	✓
		Dark Gray Blue	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Mustard	✓	✓		✓		✓		✓		✓		✓	✓	✓
		Brown	✓	✓		✓	✓	✓		✓		✓		✓	✓	✓
		Reddish Brown	✓	✓		✓	✓	✓		✓		✓		✓	✓	✓

Table C9. Testing the Predicted Track Line and MinSep Lines for Compliance with Segmentation Requirements

Color 1	Color 2	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
	Black														
	Dark Gray Blue														
	Dark Mustard														
	Dark Gray (Gray 38)														
White	Brown														
	Reddish Brown														
	TPA Blue			✓											
	Deep Sky Blue														
	Yellow (30%)	–	✓*	–		–		–		–		–		–	

Table C10. Testing Primary Targets for Compliance with Segmentation Requirements

System	Color 1	Color 2	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
STARS	Search Target Blue	Green														
		Black		✓										✓		✓
		Dark Gray Blue	✓	✓				✓	✓	✓	✓	✓		✓		✓
		Dark Mustard	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Gray (Gray 38)		✓						✓		✓		✓		✓
		Brown	✓	✓					✓	✓	✓	✓	✓	✓	✓	✓
		Reddish Brown	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
		History Blue 1		✓		✓*		✓*				✓		✓		✓
CARTS	Deep Sky Blue	Green	✓	✓							✓					✓
		Black														
		Dark Gray Blue														
		Dark Mustard		✓												✓
		Dark Gray (Gray 38)	✓													
		Brown	✓		✓											
		Reddish Brown	✓		✓											✓

Table C11. Testing History Trails for Compliance with the Pattern and Regional Segmentation Requirements

Color 1	Color 2	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
History Trails 1	History Trails 2	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Black		✓				✓		✓		✓		✓	✓	✓
	Search Target Blue	✓	✓				✓				✓		✓		✓
	Deep Sky Blue														
	Dark Gray Blue	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Dark Mustard	✓	✓		✓		✓		✓		✓		✓	✓	✓
	Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Brown	✓	✓		✓	✓	✓		✓		✓		✓	✓	✓
	Reddish Brown	✓	✓		✓	✓	✓		✓		✓		✓	✓	✓
History Trails 2	History Trails 3	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓	✓
	Black		✓		✓		✓				✓		✓	✓	✓
	Search Target Blue	✓	✓								✓		✓		✓
	Deep Sky Blue														
	Dark Gray Blue	✓	✓		✓		✓		✓		✓	✓	✓	✓	✓
	Dark Mustard	✓	✓		✓		✓				✓		✓		✓
	Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Brown	✓	✓		✓		✓		✓		✓		✓		✓
	Reddish Brown	✓	✓		✓		✓		✓		✓		✓		✓
History Trails 3	History Trails 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Black	✓	✓		✓		✓		✓	✓	✓		✓	✓	✓
	Search Target Blue	✓	✓										✓		✓
	Deep Sky Blue														
	Dark Gray Blue	✓	✓		✓		✓				✓		✓	✓	✓
	Dark Mustard		✓				✓						✓		✓
	Dark Gray (Gray 38)	✓	✓		✓		✓		✓		✓		✓	✓	✓
	Brown		✓		✓		✓				✓		✓		✓
	Reddish Brown	✓	✓				✓				✓		✓		✓

(table continues)

Table C11 (continued). Testing History Trails for Compliance with the Pattern and Regional Segmentation Requirements

Color 1	Color 2	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
History Trails 4	History Trails 5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Black	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Search Target Blue	✓	✓										✓		✓
	Deep Sky Blue														
	Dark Gray Blue	✓	✓				✓				✓		✓		✓
	Dark Mustard		✓										✓		✓
	Dark Gray (Gray 38)	✓	✓		✓		✓		✓		✓		✓	✓	✓
	Brown		✓				✓				✓		✓		✓
	Reddish Brown		✓				✓				✓		✓		✓
History Trails 5	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Search Target Blue	✓	✓										✓		✓
	Deep Sky Blue														
	Dark Gray Blue		✓				✓				✓		✓		✓
	Dark Mustard		✓										✓		✓
	Dark Gray (Gray 38)	✓	✓		✓		✓		✓		✓		✓	✓	✓
	Brown		✓				✓						✓		✓
	Reddish Brown		✓				✓				✓		✓		✓

Table C12. Testing Weather in Lists and Highlighted Text for Compliance with Segmentation Requirements

Display Element	**System**	**Color 1**	**Color 2**	**B1**	**B2**	**T1**	**T2**	**T3**	**T4**	**S1**	**S2**	**S1**	**S2**	**F1**	**F2**	**F3**	**F4**
Weather in lists	STARS	Cyan	Green		✓						✓		✓		✓		✓
Highlighted text in toolbar		Yellow	White		✓						✓		✓		✓	✓	✓

Table C13. Testing J-rings and J-cones for Compliance with Segmentation Requirements

Color 1	Color 2	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
TPA Blue	Black		✓				✓		✓		✓		✓		✓
	Dark Gray Blue	✓	✓		✓		✓		✓		✓	✓	✓	✓	✓
	Dark Mustard	✓	✓		✓		✓		✓		✓		✓	✓	✓
	Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Brown	✓	✓		✓		✓		✓		✓	✓	✓	✓	✓
	Reddish Brown	✓	✓		✓		✓		✓		✓		✓	✓	✓
	Green (Range Bearing Line)				✓										
	White														

Table C14. Testing Text Colors for Compliance with the Text Legibility Requirements

Display Element	Text Color	Background/ Contrast Color	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Owned Datablocks	White	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Gray Blue	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Mustard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Reddish Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Yellow														
		Yellow (30%)	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓
Unowned Datablocks, Lists, List Titles	Green	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Gray Blue	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Mustard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Reddish Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Yellow														
		Yellow (30%)	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓
Lists, List Titles	Green 4	Black	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
		Dark Gray Blue														
		Dark Mustard														
		Dark Gray (Gray 38)											✓		✓	
		Brown														
		Reddish Brown														
		Yellow	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Yellow (30%)	–		–		–		–		–		–		–	

(table continues)

Table C14 (continued). Testing Text Colors for Compliance with the Text Legibility Requirements

Display Element	Text Color	Background/ Contrast Color	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Pointouts	Yellow	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Gray Blue	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Mustard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Reddish Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Yellow (30%)	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓
Alert Datablocks	Red	Black	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dark Gray Blue											✓	✓	✓	✓
		Dark Mustard														
		Dark Gray (Gray 38)				✓		✓		✓		✓	✓	✓	✓	✓
		Brown						✓						✓		✓
		Reddish Brown														
		Yellow	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Yellow (30%)	–		–		–	✓	–		–		–	✓	–	✓

Table C15. Testing Proposed Alternative Text Colors for Compliance with the Text Legibility Requirements

Text Color	**Background/ Contrast Color**	**B1**	**B2**	**T1**	**T2**	**T3**	**T4**	**S1**	**S2**	**S1**	**S2**	**F1**	**F2**	**F3**	**F4**
Test Red 1	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray Blue				✓		✓					✓	✓	✓	✓
	Dark Mustard				✓								✓		✓
	Dark Gray (Gray 38)	✓	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓
	Brown				✓		✓					✓	✓		✓
	Reddish Brown														
	Yellow	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Yellow (30%)	–		–	✓	–	✓	–		–		–	✓	–	✓
Test Red 2	Black	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray Blue				✓		✓					✓	✓	✓	✓
	Dark Mustard				✓								✓		✓
	Dark Gray (Gray 38)			✓	✓		✓		✓		✓	✓	✓	✓	✓
	Brown				✓		✓					✓	✓		✓
	Reddish Brown														
	Yellow	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Yellow (30%)	–		–	✓	–	✓	–		–		–	✓	.	✓
Test Red 3	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray Blue				✓		✓					✓	✓	✓	✓
	Dark Mustard				✓								✓		✓
	Dark Gray (Gray 38)		✓	✓	✓		✓		✓		✓	✓	✓	✓	✓
	Brown				✓		✓						✓		✓
	Reddish Brown														
	Yellow	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Yellow (30%)	–		–	✓	–	✓	–		–		–	✓	–	✓

(table continues)

Table C15 (continued). Testing Proposed Alternative Text Colors for Compliance with the Text Legibility Requirements

Text Color	Background/ Contrast Color	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Test Red 4	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray Blue				✓		✓					✓	✓	✓	✓
	Dark Mustard				✓								✓		✓
	Dark Gray (Gray 38)		✓	✓	✓		✓		✓		✓	✓	✓	✓	✓
	Brown				✓		✓						✓		✓
	Reddish Brown														
	Yellow	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Yellow (30%)	–		–	✓	–	✓	–		–		–	✓	–	✓
Test White 1	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray Blue	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Mustard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Reddish Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Yellow														
	Yellow (30%)	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓
Test White 2	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray Blue	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Mustard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Reddish Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Yellow														
	Yellow (30%)	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓

(table continues)

Table C15 (continued). Testing Proposed Alternative Text Colors for Compliance with the Text Legibility Requirements

Text Color	Background/ Contrast Color	B1	B2	T1	T2	T3	T4	S1	S2	S1	S2	F1	F2	F3	F4
Orange	Black	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray Blue	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Mustard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Dark Gray (Gray 38)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Reddish Brown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Yellow		✓		✓		✓		✓		✓	✓	✓	✓	✓
	Yellow (30%)	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓	–	✓