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Reexamination of Color Vision Standards, Part III: Analysis of the Effects of Color Vision Deficiencies in Using ATC Displays

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16. Abstract

The purpose of this report is to assess the effect of color use in air traffic control (ATC) displays for users who have color vision deficiencies, denoted as color deficient (CD). At present, color is extensively used in many ATC displays, while the color vision standard used by the Federal Aviation Administration (FAA) allows certain types of CDs to enter the ATC workforce. Many guidelines for color use in visual displays state that color use should be accompanied with achromatic redundant cues to avoid misinterpretation by CD users. However, little has been documented in guidelines about the effect of redundant cues. Therefore, it is necessary to understand how CD personnel use color-coded information in displays and whether redundant cues are helpful. Previously, we collected data about color use in displays from many ATC facilities. We also developed computational algorithms that could assess the effects of color vision deficiencies on the performance of color-related ATC tasks. The algorithms compared the effectiveness of using color-coded information between observers with normal color vision and CDs. The algorithms also considered the effectiveness of redundant visual cues relative to colors. In this report, we applied the algorithms to six ATC displays to estimate their efficient use by CDs. The main findings included the following: 1) Critical color-coded information may not capture the attention of CDs in many applications; 2) There are instances where CDs may not reliably identify types of information that are encoded in colors; and 3) In many instances color use makes text reading slower and less accurate for CDs. These results indicate that CDs may not be able to use color displays as efficiently as users with normal vision. In addition, we identified the situations where no redundant cues were used for task-critical color usages. Moreover, we estimated that most redundant cues were not as effective as color or not effective at all for the given task.

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Reexamination of Color Vision Standards, Part III: Analysis of the Effects of Color Vision Deficiencies in Using ATC Displays

INTRODUCTION

About 8-10% of all males have various degrees of color vision deficiency, which makes them unable to discriminate between colors that appear different to people with normal color vision. This report is a continuing effort to reexamine the FAA's color vision standards and focuses on the effect of color vision deficiencies on using air traffic control (ATC) displays. In our previous studies (Xing & Schroeder, 2005a,b), we observed color use at nine ATC facilities: three airport control towers, three Terminal Radar Approach Control (TRACONS) facilities, and three en route ATC centers. The results revealed extensive color use of ATC displays. We then developed a set of algorithms to compute the effect of color vision deficiencies. In the current report, we applied the algorithms to six major ATC displays, and we analyzed the effects of color use on task performance of air traffic controllers who have color deficiencies.

The color vision standard used by the FAA may not adequately cover the scope of color use in current ATC displays (Xing & Schroeder, 2005a). To understand whether the standard is sufficient for current task requirements associated with color use, it is essential to understand the effect of color vision deficiencies on using color displays. Given that many color displays are being used in ATC facilities, it is not practical to run a study by recruiting a group of color-deficient controllers to perform ATC tasks using all of the current displays. Therefore, in the previous report, we developed a set of computational algorithms to assess the potential effect of color on the performance of individuals with color vision deficiencies, denoted as color deficient (CD), relative to personnel with normal color vision, denoted as color-normal (CN). The algorithms used a computational method that simulated colors as seen by deuteranopes and protanopes, the two major types of CDs (Brettel, Vienot, & Mollon, 1997; Vienot, Brettel, & Mollon, 1999). The algorithms allowed us to assess the efficiency of color displays for CDs by calculating the effectiveness of color for CDs in a given task. By applying the algorithms to existing ATC displays, we can identify the situations where color use could be a potential problem for CD controllers, and high-fidelity experiments can be focused on those situations to examine the exact effects of color on CDs' task performances.

Our previous study (Xing & Schroeder, 2005a) has shown that colors on ATC displays are used for three purposes: 1) to capture attention; salient colors are often chosen to encode information that needs to be attended to immediately, such as an alert or emergency; 2) to identify categories of information so that searching for specific information in a complex image can be done more effectively; in this case, each color is associated with a distinctive meaning; and 3) to segment complex images in a display into distinctive groups so that information belonging to the same category can be organized together. In this application, color does not have inherent meanings. Therefore, we use three terms to refer to color-related tasks throughout this report: *attention, identification,* and *segmentation.* In addition, since reading text is an important part of many ATC tasks, and the efficiency of reading is affected by color use, we also analyzed the effect of color in text reading.

This report describes our analysis of the effect of color vision deficiencies on the use of ATC displays. We analyzed the effect for several primary displays with which controllers handle aircraft, and several widely used supporting displays from which controllers acquire additional information for decision-making. Finally, we conducted an analysis of the overall effects of color vision deficiencies on ATC task performance. The results provide insights into the color vision deficit problem in using existing ATC displays and suggest the need for further task analysis and experimental studies.

METHODS

Data Acquisition

The data on color use in this study are mainly acquired from the pictures of ATC displays we took during our facility observations (Xing & Schroeder, 2005a). For circumstances where the resolution of the digital pictures was low or where some colors were not available at the time of observations (e.g., color-coded weather information), we used other sources of information to re-create the images of color displays. Those sources included: 1) color descriptions recorded during facility observations; 2) color specifications obtained from manufacturers; and 3) interface descriptions of the displays.

ATC displays

We analyzed the effects of color vision deficiencies for all the primary displays currently used by operational controllers to control aircraft. The primary display in en route ATC centers is Display System Replacement (DSR) for inland airspace or the Advanced Technologies and Oceanic Procedures (ATOP) for oceanic airspace. Unfortunately, data about ATOP were not available because it was not in full operation at the time of our facility observation. The primary displays for TRACONs are Standard Terminal Automation Replacement System (STARS) and Automated Radar Terminal System (ARTS) Color Display (ACD). For airport control towers, while controllers do not use radar displays to control aircraft, it is crucial for controllers to acquire accurate weather and traffic information in a timely manner. Thus we analyzed the Integrated Terminal Weather System (ITWS) being used in many control towers. In addition, the User Request Evaluation Tool (URET) and Traffic Management Advisor (TMA) are two major support tools for en route controllers to acquire additional information. Since URET and TMA are being used or are scheduled to be deployed to many en route facilities, they were chosen to represent supporting tools for our analysis.

Review of the algorithms

We previously developed a set of algorithms to assess the effect of color vision deficiencies by considering two factors: achromatic redundant cues and color for CDs. Presumably, if either works, then CDs should have no problem using color displays. Hence, the analysis of color use included determining the effect of redundant cues relative to colors and computing the effect of colors for CDs relative to CNs. Taking the two factors together, the algorithms provide an overall assessment about how CDs use color displays.

Effect of redundant cues relative to color

When achromatic visual features are used to identify information in addition to color, those features are considered to be redundant cues. While it is desirable that CDs can use redundant cues to acquire color-coded information, the effect of redundant cues may not be the same as that of color for a given task. We synthesized the data in the literature about the effectiveness of achromatic visual features relative to color. For attention tasks, flashing and brightness are equivalent to or more effective than color, while shape and text are not effective in general (Christ, 1975). A sudden onset of color and luminance can also draw attention under some circumstances (Yantis & Jonides, 1996). For identification tasks, color is superior to achromatic cues such as location, shapes, and text, while luminance and size are not effective (Young & Nagy, 2003; Christ, 1975). Some ATC displays employed another type of redundant cue: Although no achromatic features are visually present along with color use, color-coded information can be inferred from other parts of the displays. We refer to such cues as "inference" redundant cues. They are less effective than color in terms of the time and the amount of brain processing required to comprehend the information.

Effects of color for CDs relative to CNs

The effects of color in attention, identification, and text readability may depend on the chromaticity, luminance, or both. In general, the effectiveness of color increases with the luminance and /or chromaticity difference between the color-coded targets and other materials in a display. In the preceding report, we synthesized the data in the literature and determined the threshold of luminance or chromaticity difference, below which the use of color was not effective for a given task. The results are summarized as follows:

- The effect of color in attention tasks depends on visual conspicuity of the target, which, in turn, depends on chromaticity and luminance differences between the target and other materials presented in the visual field. Those materials are denoted as distracters. The threshold point for luminance difference is $20 cd/cm^2$. The threshold point for chromaticity difference is 0.24 in CIE (Commission Internationale de l'Eclairage) chromaticity coordinates (Nagy & Sanchez, 1990; 1992).
- The effect of color in identification tasks depends on the chromaticity differences between colors and how well the colors can be named. The threshold difference for identification is 0.036 in CIE chromaticity coordinates. Below the threshold, two colors cannot be named distinctively (Smallman & Boynton, 1990; Boynton, MacLaury, & Uchikawa, 1989).
- Text readability is defined as the property that permits an observer to read text easily on a screen irrespective of the text meaning. It mainly depends on the luminance contrast between the text and background colors (Legge, Parish, Luebker, & Wurm, 1990). Readability is typically measured as the time required to find and read a given text or the number of words read per minute. Many experiments have demonstrated that reading speed decreases as the text contrast decreases. Below 20% contrast, reading speed slows down much more rapidly and is significantly below the normal reading speed (Legge et al., 1990; Scharff & Ahumada, 2002). Thus, the threshold contrast for reading is usually taken as 20%.

Algorithms

We applied the algorithms to ATC displays using the following steps:

1) Determine situations where color-coding is associated with a task.
2) Determine achromatic redundant cues.
3) Determine the effectiveness of redundant cues relative to that of color.
4) Determine color specifications for the targets, distracters, and background. The specifications are the digital values of the three monitor color channels, denoted as *r* for red, *g* for green, and *b* for blue.
5) Determine the default color, which is the dominant color of distracters.
6) Determine the effectiveness of color for CDs relative to CNs.
7) Combine the effect of redundant cues and the effect of color for CDs to determine the overall effectiveness of color use.

In the previous report (Xing & Schroeder, 2005b), we classified the effect of CDs into three levels: "E" was denoted for the situation where color was equally or more effective for CDs than for CNs; "L" represented the situation where color was less effective for CDs than for CNs; and "NE" meant that color was not effective for CDs. Similarly, we categorized the effect of redundant cues into three levels: "E" was denoted for the situation where a redundant cue was equally or more effective than color; "L" represented the situation where a redundant cue was less effective than color; and "NE" meant that a redundant cue was not effective. We continue to use these three-level scales to describe the results in this report. In addition, "NA" is used to denote situations where a redundant cue is "not available."

RESULTS

We were mainly concerned with how color use affected ATC task performance for CDs; thus, the analysis in this section focused only on colors associated with important ATC tasks. Specifically, only the situations where color was used as the primary cue for attention and identification were considered in the analysis.

Most ATC displays are complex, and information is not static. To make a systematic analysis and avoid missing important color usages, we analyzed color use by functional components of a given display. Typical components in ATC displays included datablocks, targets, boundaries, menus, weather, etc.

Automated Radar Terminal System Color Display (ACD)

ACD is a primary display used by operational controllers at selected TRACON and tower facilities. It provides controllers with a stable, high-resolution color display of aircraft positions and a graphical user interface for control functions. Among the display components, datablocks and weather use color-coding for task-critical information.

Datablocks

Datablocks are displayed across the central area of an ACD screen. The background color is dark blue. While controllers can adjust the background luminance, they usually leave it very dark, close to black. Most datablocks are either white or green. White identifies datablocks owned by a controller, and green identifies those not owned.

When the system detects a potential conflict, a flashing red text appears on the top of the datablock (such text is called "line 0" of a datablock), with "CA" indicating a conflict alert and "LA" indicating a low-altitude alert. Once the alert is acknowledged, controllers click the datablock to stop it from flashing. The alert text remains red until the conflict is resolved. Thus, red is first used to draw attention to a conflict. This purpose is also served by flashing as a redundant cue. There are two additional redundant cues to alert controllers of emergency situations on line 0. One is an audible alarm that sounds until the alert is acknowledged. The second is a conflict alert list that lists those targets in tabular form that are in conflict or low altitude alert. After a controller acknowledges the presence of a conflict by stopping the flashing, the alert message remains red for the controller to identify the aircraft that is in conflict, so red is also used for identification.

Two colors are used for datablocks to indicate the ownership of aircraft: White datablocks are for owned aircraft, the ones for which the controller is responsible; green datablocks are for unowned aircraft, the ones that the controller does not control. Ownership is also indicated by a position symbol (a letter representing the sector that the controller is working with) attached to the datablock. Thus, white and green are used for identification, with text being the redundant cue.

Yellow is used to identify datablocks of aircraft that are of interest to other controllers. The datablock of an aircraft owned by controller A is white on controller A's display and depicts a full datablock. The datablock of the same aircraft is green on controller B's display and is depicted by a partial datablock. When controller A needs to point out that aircraft to controller B, controller A can initiates a "pointout" action which means the datablock becomes a full datablock on B's display, turns yellow in color, the letters PO appear at the end of line two, and the entire datablock flashes. When controller B acknowledges the pointout by slewing the cursor over the datablock and depressing the left acknowledge key, the datablock stops flashing, goes to a steady state, but remains yellow in color on his display.

We first determined the background color and the default color of distracters. A default color is the color used for the majority of displayed materials in a display. Computer programmers use three numbers to specify a color: *r* for red, *g* for green, and *b* for blue. For example, the *rgb* values of red are (255, 0, 0) at its maximum luminance. Default colors are white (255, 255, 255) and green (0, 255, 255).

Next we determined the purposes of color use, followed by the computation of the effect of color for CDs relative to that for CNs. If a color was used for multiple purposes, the analysis was performed for each purpose separately. For example, red was used for attention and identification. The effect of red was subsequently analyzed twice, once for each purpose.

Red for attention

The purpose of using red is to draw a user's attention to an alerted datablock among many other white and green datablocks. The red-colored "Line 0" text is accompanied by flashing, which is more effective than color for attention. Therefore, the effect of the redundant cue relative to the color is classified as "E." For CDs, both the luminance difference and chromaticity difference between red and green are below the threshold for attention, so the effect of color for CDs is classified as "NE." The overall effect of the red alert messages is "E," because the flashing redundant cue is sufficient to serve the purpose even though the color use is not effective. As for text readability, even CNs cannot reliably read flashing text. Thus, the readability is classified as "NA."

Red for identification

After a controller acknowledges the alert and stops the flashing, the alert text remains red for the controller to identify the conflicting datablocks from those in white, green, and yellow. The red text in "Line 0" of the datablock is either "CA" for collision alert or "LA" for low altitude alert. In addition, there is text in a conflict alert list that lists those targets in tabular form that are in conflict or low altitude alert. Thus, these two forms of text can serve as redundant cues for the color; however, they are less effective than color in identifying information. In addition, since the alert message "CA" or "LA" always appears in the position "Line 0" (which is on the top of a datablock), location serves as another redundant cue. Location is also less effective than color. For CDs, the chromaticity difference between red and green is below the threshold for identification; thus, red is not effective for differentiating datablocks from those in green. The overall effect of red alert messages in identification is categorized as "L" because of the effect of the redundant cues. The luminance contrast between the red text and dark background is below the reading threshold, even for CNs. Thus, the readability belongs to the "NE" category. Consistent with this finding, many controllers believe that red alert messages are difficult to read.

Yellow for identification

The purpose of yellow is to identify point-out datablocks from white and green ones. The redundant cues are flashing and the text "PO" before a controller acknowledges it and only the text PO remains after the acknowledgement. The effectiveness of the text redundant cue for identification is "L". Since CDs cannot reliably name yellow from green, yellow is not effective for the task purpose. Therefore, the overall effect of yellow is classified as "L" in identifying datablocks for CDs. Since CDs perceive about the same luminance of yellow as CNs do, the yellow text on a dark background renders equivalent text readability for both CDs and CNs.

Green for identification

Green and white are used to identify ownership of aircraft with which datablocks are associated. Green identifies the aircraft as unowned by the controller. A letter called the position symbol also indicates the ownership of an aircraft. The position symbol indicates the sector or position that has control of an aircraft. It is superimposed on the target and beacon symbol. A leader line extends from the target/beacon symbol/position symbol to the datablock. Thus, the position symbol can serve as a redundant cue, although it is less effective than color in complex scenes. For CDs, green is less effective to identify targets than white. The overall effect is "L" because both the redundant cue and the color for CDs are less effective. CDs can read the green text on a dark background as well as CNs do.

Weather on ACD

Filled background areas in the traffic situation display represent weather information. ACD has six weather levels: Levels 1-2 for moderate, Levels 3-4 for heavy, and Levels 5-6 for severe weather. It is crucial for controllers to distinguish different weather levels. Weather levels are represented by color and shades. Levels 1-2 are gray, Levels 3-4 are orange, and Levels 5-6 are orange-red. The areas with Levels 1, 3, and 5 weather are uniformly filled with the corresponding color. The areas with Levels 2, 4, and 6 weather are filled with the corresponding color and white stipples. It is desirable for controllers to notice heavy weather immediately. Thus, orange and orange-red colors are used to draw attention and to identify the more severe types of weather.

Without color information, the only way controllers can identify weather levels is through the weather buttons in the menu bar on the top of an ACD display. Three menu buttons are toggle switches for weather Levels 1-2, 3-4, and 5-6, respectively. If a controller could not identify a weather level by its color, he/she could turn on and off the weather buttons to determine the level. However, that is a tedious procedure. Controllers usually turn off Level 1-2 weather and leave levels 3-4 and 5-6 on all the time. In this situation, although no redundant visual cues are associated with the color-coded objects, controllers can infer the information from the cues in other parts of the display. We refer to such cues as "Inference."

Orange and orange-red for attention

The color orange is specified with the *rgb* values of (139, 90, 0). Orange-red is specified with (205, 55, 0). The shape of a filled weather area appears different from other materials such as datablocks, aircraft symbols, or boundaries. Thus, such a filled area may draw attention if it is significantly larger than the distracters; however, the shape cue is still less effective than color, so the effect of the redundant cue is categorized as "L" or "NE." For CDs, orange and orange-red are not effective in drawing attention from white and green distracters because of their lower luminance and weak color difference from green. The overall effect is "L," as determined by the effect of the redundant cue.

Orange and orange-red for identification

Another purpose of these two colors is to identify Levels 3-4 and Levels 5-6 from Levels 1-2 (gray) weather. The redundant cue is the inference from the weather-level buttons in the menu bar. The effectiveness of such an inference cue is less than that of color. For CDs, the chromaticity differences between orange and orange-red, orange and gray, as well as orange-red and gray are all above the identification threshold but are less for CDs than CNs. Thus, the overall effect is classified as "L."

Since filled weather areas overlay the situation display, the text readability of datablocks is a concern for weather displays. While controllers should be able to read datablocks through filled weather areas, the readability of green datablocks on an orange or orange-red weather background is below the reading threshold. Fortunately, in real operations, aircraft rarely fly into heavy weather because a controller would re-route the aircraft. Thus, readability of datablocks in a weather area may not be a practical issue of concern.

Results of color use for ACDs are summarized in Table 1. The results for each color usage are listed in a row.

Table 1. Analysis of color use in ACD.

Display Component		Color	Usage	Purpose	Redundant Cue	Eff-R	Eff-C	Overall Effect	Text Readability
Datablock	Alert	Red	Text	Att.	Flashing	E	NE	E	NA
	Alert	Red	Text	Id.	Text / Location	L	NE	L	NA
	Pointout	Yellow	Text	Id.	Text	L	NE	L	E
	Unowned aircraft	Green	Text	Id.	Text	L	L	L	E
Weather	Level-3,4	Orange	Filled area	Att.	Shape	L / NE	NE	L	NA
	Level-3,4	Orange	Filled area	Id.	Inference	L	L	L	NE
	Level-5,6	Orange-red	Filled area	Att.	Shape	L / NE	NE	L	NA
	Level-5,6	Orange-red	Filled area	Id.	Inference	L	L	L	NE

Eff-R – Effect of redundant cues relative to colors.

Eff-C – Effect of colors for CDs relative to CNs.

Att. – attention.

Id. – identification.

L / NE – The effect could belong to either category depending on other attributes of the colored target such as the size or shape.

If a color is used for both attention and identification, the results for that color are listed in separate rows. The information presented in Table 1 columns, from left to right, includes the following:

- Display component: The functional component of a display.
- Color: The color used in the component.
- Usage (of color): The visual stimuli that a color is applied to, such as text, box frame, symbol, filled area, or line.
- Purpose: The purpose of color use (attention or identification).
- Redundant cue: The achromatic visual attributes that are used along with the color.
- Eff-R: The effect of the redundant cue relative to the color.
- Eff-C: The effect of color for CDs relative to CNs.
- Overall effect: The overall effect by considering Eff-R and Eff-C together.
- Text readability: The readability of the text associated with the color use.

Standard Terminal Automation Replacement System

STARS uses more colors than other primary ATC displays. Essentially every component in a STARS display involves color. The components where color use is task-critical include system status alert, datablocks, weather, geographic restricted area, coordination list, and target symbol. We analyzed the use of color in these components, described the results, and summarized them in Table 2.

System status alert

The STARS display has a text box to indicate the system status. Within the box there are text fields for system failure alert, system overload alert, and radar failure alert. A text field is blank if there is no alert. If an alert is detected, red text appears in the corresponding field. Thus, red is used to draw the controller's attention to the alert. The background of the text box is black. The default colors of other materials in the area are white and gray, which are the text colors in other menu boxes.

Red for System Status Alert attention

Red is used to draw attention to alert messages. The redundant cue is the onset of the alert texts in a fixed location. The texts are not effective for attention. The onset of the texts may be able to draw attention, but the effect is less than that of color. For CDs, red is not effective to draw attention from white distracters. The overall effect is "L." The luminance contrast of the red texts on a black background for CDs is below the reading threshold, so we classified the readability as "NE."

Datablocks

The default color for datablocks is green. A controller can highlight a specific datablock by clicking it to temporarily change the color to white. The alert messages for potential conflicts are similar to those on the ACD. Other than the red text of "CA" for conflict alert and "LA" for low altitude alert in "Line 0," the alert messages of STARS also include several other types of alerts, all displayed in flashing red. Here, red is used for attention. Its effectiveness for CDs is "NE" due to the low luminance.

Aircraft symbol

An aircraft symbol on STARS can be a Search Target Symbol (primary), or a Beacon Target Symbol (secondary), or both. The symbol consists of a small 2-dimentional graphic shape. The Search Target Symbol is displayed in green, and the Beacon Target Symbol is displayed in bright yellow. Thus, the purpose of yellow and green is to identify types of symbols. The chromaticity difference between green and yellow for CDs is below the identification threshold, thus the effect is "NE." No visual redundant cue is used for the two types of symbols. However, controllers can infer the target type from the associated datablock. Therefore, the effect of the redundant cue is "L." Taken together, the overall effect of color use in aircraft symbols is "L."

Weather

Weather information is presented on STARS with filled background areas that overlay the datablocks and other symbols. Because it must be possible to see aircraft datablocks, list data, radar targets, position symbols, history trails, and map data through the weather data, weather information on STARS is drawn with two low-luminance colors. Up to six levels of weather precipitation are displayed independently or simultaneously based on the users' selection from the Display Control Bar. Weather levels are displayed as filled background areas using combinations of overlay stipples and color. Thus, controllers can determine each weather level in isolation based on the coding used. The coding schemes for weather levels are as follows:

- Weather Level 1 - Dark gray-blue
- Weather Level 2 - Dark gray-blue, low-density bright gray overlay stipple
- Weather Level 3 - Dark gray-blue, high-density bright gray overlay stipple
- Weather Level 4 – Dark mustard
- Weather Level 5 – Dark mustard, low-density bright gray overlay stipple
- Weather Level 6 – Dark mustard, high-density bright gray overlay stipple

Table 2. Analysis of color use in STARS.

Display Component		Color	Usage	Purpose	Redundant cue	Eff-R	Eff-C	Overall Effect	Text Readability
System Status Alert	Alert	Red	Alert	Att.	Location	L	NE	L	NE
Datablock	Alert	Red	Alert	Att.	Flashing	E	NE	E	NA
	Alert	Red	Alert	Id.	Text/ location	L	L	L	NE
Aircraft Symbol	Primary target	Green	2-D graphic symbol	Id.	Inference	L	NE	L	NA
	Secondary target	Yellow	2-D graphic symbol	Id.	Inference	L	NE	L	NA
Weather	Levels- 1,2,3	Dark Gray-blue	Filled area	Id.	Inference	L	L	L	E
	Levels- 4,5,6	Dark Mustard	Filled area	Id.	Inference	L	L	L	E
Coordination List	Message status	Green	Text	Id.	None	NA	NE	NE	E
	Message status	Yellow	Text	Id.	None	NA	NE	NE	E
Restriction Area		Beige	Filled area	Id.	Shape	E	E	E	L

The dark gray-blue is specified with the *rgb* values (57, 115, 115) and dark mustard is specified with (124, 124, 64). Since the three lower levels (Levels 1, 2, 3) use the same texture patterns as the three higher levels (Levels 4, 5, 6), color is the only visual cue that distinguishes between lower and higher levels. Without color, a controller still can identify the weather level by selectively turning on and off the weather-level selection boxes in the Display Control Bar. Nevertheless, the procedure is tedious; thus, the effectiveness is less than what would be produced by color.

Dark gray-blue and dark mustard for identification

The purpose of the colors is to identify weather levels. The redundant cue is the inference from weather-level selection boxes in the menu bar. The chromaticity difference between dark gray-blue and dark mustard for CDs is above the identification threshold but is less than the difference for CNs. Thus, the overall effect is classified as "L." The text readability of green datablocks on a gray-blue or mustard background is about the same for CDs as for CNs.

Coordination list

The coordination list provides information about the coordination status between controllers. Three colors are used to identify the status of text messages: white for unsent messages, green for acknowledged messages, and yellow for non-acknowledged messages. No redundant cues are used. CDs perceive white and yellow in roughly the same way as CNs do. However, CDs perceive green as dark yellowish. The chromaticity difference between yellow and green for CDs is below the identification threshold. Thus, the two colors are not effective for identification. The text readability is about the same for CDs as that for CNs.

Geographic restriction area

A geographic restriction area is indicated with a circle or polygon filled with beige color, specified by *rgb* values of (225, 150, 90). The text displayed within the circle or polygon is green. Although beige is used to identify geographic restriction areas, the shapes of such areas are distinctive from other materials in the display and can be reliably named (circle or polygon), so they are as effective as color for the identification purpose. Thus, we classify the effect of the redundant cue as "E." The readability of the green text on a beige background is less for CDs than that for CNs.

Display System Replacement

Presently, DSR does not use many colors. The background color of a DSR can be adjusted between dark blue and black. Datablocks are green. Conflict alerts are indicated by flashing texts; no color cues are utilized. Currently, only two components of a DSR display use color-coding: the graphic tool and the Weather And Radar Processor (WARP). The use of color in these two components is described below and summarized in Table 3.

Graphic tool

The graphic tool allows controllers to select one of the four given colors to draw filled areas for specific flying regions. The four colors are red, yellow, green, and white. The distance of a chosen aircraft to a specified region is subsequently displayed with the same color. Thus, the colors are used to identify information. For CDs, the chromaticity differences between red and green, red and yellow, as well as green and yellow are all below the identification threshold. Therefore, red, yellow, and green are not effective. In addition, the readability of red text on a dark blue background is below the reading threshold.

Weather And Radar Processor

WARP displays specialized aviation weather products to support en route air traffic control operations. It provides Next Generation Doppler Weather Radar (NEXRAD) data for DSR displays. NEXRAD data are classified into six weather levels. Levels 1-2 are moderate weather, and levels 3-6 are heavy weather that requires controllers' im-

Table 3. Analysis of color use in DSR.

Display Component		Color	Usage	Purpose	Redundant Cue	Eff-R	Eff-C	Overall Effect	Text Readability
Graphic Tool		Red	Filled area/ Text	Id.	NA	NE	NE	NE	NE
		Yellow	Filled area/ Text	Id.	NA	NE	NE	NE	E
		Green	Filled area/ Text	Id.	NA	NE	NE	NE	E
Weather	Levels 1,2	Purple	Filled area	Id.	Text	L	NE	L	NE
	Levels 5,6	Turquoise	Filled area	Id.	Text	L	NE	L	NE

mediate attention. Two colors and one colored pattern are used to display NEXRAD data in filled background areas on the DSR: purple for Levels 1-2, turquoise and black checkerboard for Levels 3-4, and turquoise for Levels 5-6. The number of each level is displayed in white overlaying on the filled weather areas.

Turquoise and purple for weather identification

The purpose of these two colors is to identify weather levels. The white text is a redundant cue indicating the weather level. The text is less effective than colors in identification. The chromaticity difference between turquoise and purple is below the identification threshold even for CNs. Thus, the effect of the colors is classified as "NA." The overall effect is "L." The readability of the white text on turquoise and purple backgrounds for CDs is roughly the same as that for CNs. However, the readability of green datablocks on a turquoise or purple background is below the reading threshold.

User Request Evaluation Tool

URET has three display windows that are frequently used by controllers: Aircraft List, Graphic Display, and Plans Display. The background color for each window is black. The default color is white. Next, we described the use of color in the three windows and summarized the results in Table 4.

Aircraft List

The Aircraft List displays several types of text information, including flight status, flight ID, altitude, and routes. Flight status is indicated with text boxes in the three left-most columns. The frames of the boxes and the text within the box are color-coded by red / muted red, yellow / muted yellow, cyan, and brown. In the first column, the boxes may be colored red or muted red. Red represents predicted loss of separation within 5 minutes. Muted red represents predicted loss of separation if the controller does not take other expected actions first. In other words, unless the controller takes some action, a loss of separation will develop. Therefore, both red and muted red serve as alerts that require controllers' immediate attention. The text box for a flight in the normal status is shown as a white box frame without text in it. When the loss of separation is predicted, the box frame turns red or muted red, and a letter "R" appears in the box in the same color as the box frame. In the second column, yellow and muted yellow represent potential conflicts between aircraft predicted to come within 5-12 minutes of each other. Thus, yellow also requires attention. In addition, each of these colors has a different meaning, and controllers must associate the color with its meaning. Therefore, we classified the purposes of these colors as attention and identification. Cyan in the third column of boxes indicates aircraft that are predicted to conflict with a restricted airspace. Brown may appear in all three columns for a single flight. Brown means that auto-prediction may not be available because no tracking data for the flight is available for URET. A brown box frame is accompanied with a symbol "X" in it, so the symbol serves as a redundant cue.

The column for flight ID uses white text for normal flights, brown for the flights without tracking data, and orange for overdue flights. No redundant cue is used. The altitude column uses white texts for filed altitude and yellow texts for inappropriate altitude. Again no redundant cue is used. Route information is displayed with white and cyan texts. Those colors are used for segmentation; thus, they are not included in the analysis below. In fact, controllers rarely rely on colors for route information because they must read the text to acquire information.

Red and muted red for attention

The redundant cue is the onset of the letter within the boxes. Because the letter is very small, its onset is not conspicuous enough to capture attention. Red is not effective to draw attention for CDs. Thus, both red and muted red are not effective for CDs.

Red and muted red for identification

While red and muted red are used to identify different types of flight status, they only differ in their luminance. The difference between them is not significant enough for CDs to reliably identify information. No redundant cue is used to tell red from muted red. Thus, the overall effect of color use is "NE." In addition, the text readability is below the reading threshold for CDs and CNs.

Yellow and muted yellow for attention

The colors are used to draw attention to flights that are predicted to come within 5-12 miles of each other. The redundant cue is a single letter "Y," which is not conspicuous enough to capture attention. Yellow is less effective to draw attention from white distracters for CDs than for CNs. The luminance difference between muted yellow and a black background is below the attention threshold even for CDs and CNs.

Yellow and muted yellow for identification

The analysis is the same as that for red and muted red in that the colors only differ in their luminance. The difference between them is not significant enough for CDs to reliably identify information. Thus, the overall effect of color use is "NE." No redundant cue is used. The readability of the yellow text on a black background for CDs is equal to that for CNs.

Table 4. Analysis of color use in URET.

Display Component		Color	Usage	Purpose	Redundant Cue	Eff-R	Eff-C	Overall Effect	Text Readability
Aircraft List	Flight status	Red	Text / Box frame	Att.	Text / Location	NE	NE	NE	NE
	Flight status	Muted red	Text / Box frame	Att.	Text / Location	NE	NE	NE	NE
	Flight status	Yellow	Text / Box frame	Att.	Text / Location	NE	L	L	E
	Flight status	Muted yellow	Text / Box frame	Att.	Text / Location	NE	L	L	E
	Flight status	Red	Text / Box frame	Id.	None	NA	NE	NE	NE
	Flight status	Muted red	Text, Box frame	Id.	None	NA	NE	NE	NE
	Flight status	Yellow	Text / Box frame	Id.	None	NA	NE	NE	E
	Flight status	Muted yellow	Text / Box frame	Id.	None	NA	NE	NE	E
	Flight status	Cyan	Text / Box frame	Id.	Text / Location	L	L	L	E
	Flight status	Brown	Text / Box frame	Id.	Text	L	L	L	NE
	Flight ID	Orange	Text	Id.	Text	L	E	E	E
	Altitude	Yellow	Text	Id.	None	NA	L	L	E
Graphic Display	Datablock / route	Red	Text / Line	Id.	None	NA	NE	NE	NE
	Datablock / route	Brown	Text / Line	Id.	None	NA	NE	NE	NE
	Datablock / route	Yellow	Text / Line	Id.	None	NA	NE	NE	E
Plan Display	Plan evaluation	Red	Text	Id.	Text	L	NE	L	NE
	Plan evaluation	Green	Text	Id.	Text	L	NE	L	E

Cyan for identification

Cyan is used to distinguish aircraft routes from those in white. The chromaticity difference between cyan and white is slightly less for CDs than for CNs. The redundant cue is the presence or absence of a letter "C" inside the text box. The cue is less effective than color. Therefore, the overall effect of cyan for CDs is "L."

Brown for identification

The purpose is to distinguish aircraft from those displayed in red, yellow, cyan, and white. The redundant cue is the presence or absence of a letter "X" in the text box. The cue is less effective than color. The chromaticity differences between brown and red, and brown and yellow for CDs are above the identification threshold but less than those for CNs. Thus, the overall effect is "L." The readability of the letter "X" for CDs is below the reading threshold.

Yellow for inappropriate altitude identification

The purpose is to highlight an aircraft's altitude from those shown in white. No redundant cue is used. The chromaticity difference between yellow and white for CDs is slightly less than that for CNs. The readability of the yellow text on a black background is about the same for CDs as that for CNs.

Graphic Display

The Graphic Display illustrates datablocks and routes for the aircraft in a sector. White datablocks and routes indicate normal flights. Red, muted red, yellow, muted yellow, brown, and cyan colors have the same meanings as those used in the Aircraft List. No redundant cues are used for the colors.

The purpose of the color use is to identify the conflict status of different types of aircraft and routes when planning a route change. For CDs, the chromaticity differences between red and brown, red and yellow, and yellow and brown are all less than the identification threshold. Thus, these colors are not effective for CDs. No redundant cue is used. The overall effect is "NE." In addition, the readability of red and brown datablocks for CDs is less than the reading threshold. The readability of yellow datablocks for CDs is equivalent to that for CNs.

Plans Display

The Plans Display shows text information about the evaluation of a proposed flight plan change. Green is used for no-confliction plans, and red indicates a conflict. The purpose of color use is for identification. The text itself is a redundant cue. However, it is less effective than colors. The chromaticity difference between red and green for CDs is below the identification threshold. Thus, the overall effect of the colors is "L." The readability of the red text for CDs is less than the reading threshold; the readability of the green text is above the threshold and equal for CDs and CNs.

Traffic Management Advisor

TMA provides a number of graphical features to improve controllers' situational awareness. The frequently used graphical features include Timeline and Load Graphs. Both use color-coding. The use of color in these two graphical products is described next, and the results are summarized in Table 5.

Table 5. Analysis of color use in TMA.

Display Component		Color	Usage	Purpose	Redundant Cue	Eff-R	Eff-C	Overall Effect	Text Readability
Timeline	Aircraft tag	Yellow	Text	Id.	None	NA	NE	NE	E
	Aircraft tag	Green	Text	Id.	None	NA	NE	NE	E
	Aircraft tag	Turquoise	Text	Id.	None	NA	L	L	E
	Delay time	Green	Text	Id.	Text	L	NE	L	E
	Delay time	Yellow	Text	Id.	Text	L	NE	L	E
	Delay time	Orange	Text	Id.	Text	L	NE	L	E
	Delay time	Red	Text	Id.	Text	L	NE	L	NE
	Delay time	Red	Text	Att.	Text	NE	NE	NE	NE
	Rush alert	Red	Graphic symbol	Att.	Shape	L	NE	L	NA
Load Graph	Traffic volume	Yellow	Curve	Id.	None	NA	NE	NE	E
	Traffic volume	Green	Curve	Id.	None	NA	NE	NE	E

Timeline

A timeline displays text information about time scales, aircraft tag, delay time, and the reference point along a double-lined vertical axis. The background color is black. The default colors are green for the majority of texts and white for the axis (lines and ticks). An aircraft tag (i.e., the code of the airline company and the flight number) may appear in one of three colors: green for normal arrivals, yellow for unfrozen Scheduled Time of Arrival (STA), and turquoise for frozen STAs. A frozen STA means that the aircraft is close enough to the meter fix that TMA schedulers will not change its STA except in response to extraordinary events. An unfrozen STA means that TMA schedulers can change the displayed STA. An orange symbol next to an aircraft tag indicates that TMA has not received any radar tracks for that aircraft so that it computes time of arrival using the filed flight plan of the aircraft.

The delay time for every aircraft is displayed as the number of minutes along the timeline. The numbers are also color-coded: green for delays less than 5 min, yellow for delays between 5 to 10 min, orange for delays between 11 to 15 min, and red for delays longer than 15 min. Thus, colors are used to identify different types of delays, yet red is also used to capture TMA users' attention. The Timeline also uses a pair of red brackets to show a rush time alert. The shape of the brackets is a redundant cue for the color.

Yellow, green, and turquoise for aircraft tag identification

The purpose of these colors is to identify different types of aircraft arrivals. No redundant cue is used. The chromaticity difference between yellow and green for CDs is below the identification threshold. The difference between yellow and turquoise is less effective for CDs than for CNs. The difference between green and turquoise for CDs is as effective as that for CNs. The text readability of these colors for CDs is equivalent to that for CNs.

Green, yellow, orange, and red for delay time identification

The purpose of these four colors is to identify four categories of delay time. The redundant cue is the text for the length of delay in minutes, and it is less effective than color. The chromaticity differences between green and yellow, green and red, as well as yellow and red for CDs, are all below the identification threshold. The differences between red and orange, as well as green and orange for CDs, are less effective than those for CNs. The readability of the red text is below the reading threshold, and the readability of the orange text is less for CDs than for CNs.

Red for attention

Red is used to draw users' attention to aircraft that have a delay time of longer than 15 minutes. It is not effective in drawing the attention of CDs. The redundant cue is the text. It is also not effective for the purpose. Thus, the overall effect of color use is "NE" for CDs. Timeline also uses a pair of red brackets to show a rush-time alert. The shape of the brackets is a redundant cue. It could draw some attention because the shape is different from other materials in the Timeline display. Nevertheless, the cue is less effective than color.

Load Graph

The Load Graph shows present and future traffic flows over time. It displays two curves: a green one for the expected traffic demand and a yellow one for planned arrivals. No redundant cue is used. In addition, a red straight line shows the airport acceptance rate. This line is static over the time. The purpose of red is neither for attention nor for identification. It is simply to segment the line from the curves because they may overlay each other.

Yellow and green for identification

The purpose of yellow and green in the Load Graph is to identify different types of traffic flows. Color is the only visual cue to distinguish the two curves, although users might be able to identify the curves based on their experience. The chromaticity difference between green and yellow for CDs is below the identification threshold, so the colors are not effective for them.

Integrated Terminal Weather System

ITWS is an automated weather information system used in TRACON and tower facilities. ITWS integrates many weather products that detect and predict windshear, microburst, gust fronts, hail, lightning, and tornadoes. The system also displays precipitation, tracks the speed and direction of storm cells, and predicts storm movements. The display components of ITWS include Graphics Product Display, Product Status Buttons, Alert Panel, and Site Information Display. We analyzed the use of color in each component and summarized the results in Table 6.

Graphics Product Display

The background color of the Graphics Product Display is gray. This product displays six levels of weather precipitation as filled areas. The intensities of precipitation are based upon National Weather Service intensity levels. Levels 1 to 6 are indicated by light green, green, yellow, light orange, orange, and red, respectively. There is no redundant cue for the colors. The Graphics Product Display also displays additional weather types such as

Table 6. Analysis of color use in ITWS.

Display Component		Color	Usage	Purpose	Redundant Cue	Eff-R	Eff-C	Overall Effect	Text Readability
Graphics Product Display	Preciptation	Light Green	Filled area	Id.	None	NA	NE	NE	NA
	Preciptation	Green	Filled area	Id.	None	NA	NE	NE	NA
	Preciptation	Yellow	Filled area	Id.	None	NA	NE	NE	NA
	Preciptation	Light Orange	Filled area	Id.	None	NA	NE	NE	NA
	Preciptation	Orange	Filled area	Id.	None	NA	NE	NE	NA
	Preciptation	Red	Filled area	Id.	None	NA	NE	NE	NA
	Preciptation	Red	Filled area	Att.	None	NA	NE	NE	NA
	Preciptation	Orange	Filled area	Att.	None	NA	L	L	NA
	Windshear Microburst	Red	Circle / Filled circle	Att.	Shape	L / NE	NE	NE	NA
	GuestFront	Purple	Solid / Dash line	Att.	Shape	L / NE	NE	NE	NA
	Windshear Microburst	Red	Circle / Filled Circle	Id.	Shape	E	NE	E	NA
	GuestFront	Purple	Solid / Dash line	Id.	Shape	E	NE	E	NA
Product Status Buttons		Red	Filled Box	Id.	None	NA	NE	NE	NE
		Green	Filled Box	Id.	None	NA	NE	NE	E
		Yellow	Filled Box	Id.	None	NA	NE	NE	E
Alert Panel	Windshear Microburst	Red	Filled Box	Att.	Luminance	E	NE	E	NE
	GuestFront	Purple	Filled Box	Att.	Luminance	E	NE	E	E
	Lightning	Yellow	Filled Box	Att.	Luminance	E	NE	E	E
Site Information Display	Airport code	Red	Filled Box	Id.	Inference	L	NE	L	E
	Airport code	Yellow	Filled Box	Id.	Inference	L	NE	L	E
	Airport code	Blue	Filled Box	Id.	Inference	L	E	E	E

microburst, wind shears, gust fronts, and tornado alerts overlaying areas of precipitation. Each of these weather types is indicated with a different color and a shape cue. Gust Fronts are displayed as solid purple lines corresponding to the location of detected gust fronts, and dashed purple lines indicate the predicted positions of the gust fronts in 10 and 20 min. A detected windshear is presented as an open red circle with the corresponding strength indicated inside the circle. A microburst is presented as a solid red circle with its strength indicated inside the circle. Detected tornadoes are presented as solid black triangles inside an open black circle in the area of detection.

Light green, green, yellow, light orange, orange, and red for precipitation identification

These filled areas vary in color from green to red to identify increasing levels of precipitation. No redundant cue is used. The hue order of these colors for CDs is different from that for CNs, so CDs may not correctly interpret precipitation levels. The chromaticity differences between many pairs of these colors are below the identification threshold. Thus, the overall effect for these colors is "NE."

Orange and red for precipitation attention

These two colors represent the heaviest precipitation levels and are intended to capture users' attention. No redundant cue is used. Red is not effective for CDs, and orange is less effective for CDs than it is for CNs.

Red and purple for severe weather attention

These colors are used to capture users' immediate attention. The distracters are the filled areas of precipitation levels; thus, the default color can vary from light green to red, depending on weather situations. In circumstances of bad weather, the precipitation areas are a mixture of green, orange, yellow, and possibly some red. Purple and red are not effective for CDs in drawing attention from such a mixture of colors. The redundant cues are the shapes (open circle, filled circle, and solid and dashed lines). The shapes usually cannot draw attention unless their size is significantly larger than that of distracters. Thus, we classified the effect as "NE."

Red and purple for severe weather identification

These colors are also used to identify severe weather. However, color is not an effective cue for identification in this display, because some colors do not uniquely correspond to one type of weather. For example, red is used for both microburst and windshear; and purple is used for the current gustfront and the gustfront predicted in 10 to 20 min. Due to the uncertainty in color-coding, most users naturally use shapes as the primary cue for identification. Thus, the effect of color in identification for CDs can be equivalent to that for CNs. The problem for CDs is that the visibility of those colored shapes becomes very low due to the shapes overlaying with color-filled precipitation areas. For example, a red circle for a windshear may not be detected by CDs if it overlays a green or red precipitation area.

Product Status Buttons

Product Status consists of two rows of buttons. Each button has texts in black, indicating the meaning of the product represented by the button. For example, "Precip" represents precipitation, and "MB" represents microburst. The color of a button represents the status of the associated weather product in Graphics Product. If a product is unavailable in the Graphics Product Display, the button turns red. If a product is available and is turned on in the Graphics Product Display, the button is green. If the product is available and is being filtered, the button is yellow. If a product is available but is turned off, the button is white. If the product is not supported, the button is gray. Therefore, red, green, yellow, white, and gray are used to identify the status of weather products. There is no redundant cue for these colors.

Red, green, and yellow for product status identification

The purpose of these colors is to identify the status of a weather product. No redundant cue is used for identification. Color differences between red and green, red and yellow, as well as green and yellow for CDs are all below the identification threshold. Thus, these colors are not effective for CDs to identify the product status. In addition, the readability of the black texts on a red background for CDs is below the reading threshold.

Alert Panel

The Alert Panel is located on the upper right-hand portion of the display. In the case of potentially hazardous weather detected in a terminal area, six boxes in this panel may light up to alert users to specific conditions. The six alert products are: Microburst Alert (red), Windshear Alert (white), Gust Front within 20 minutes (purple), Lightning Alert within 20 miles (yellow), Tornado Alert within 10 miles (black), and Anomalous Propagation (black). The background of the boxes is gray when the weather is not available. By lighting these boxes with colors, the display draws the attention of users to a situation that is potentially dangerous, or may require a change in the runway configuration or airspace. Therefore, the colors are used mainly for attention. The redundant cue is the sudden onset of colors at fixed locations. The colors also help users to identify types of weather, with location and text being the redundant cues. The default text color is black for most of the boxes but white for the purple and black boxes to render good text readability. An exception is that the text is red to draw attention for the white box when a windshear alert is detected.

Red, purple, and yellow for attention

Because the boxes in the Alert Panel form a heterogeneous field of multiple colors, these colors are not very effective in drawing attention. The redundant cue for attention is luminance. When the onset of a visual object draws attention, luminance plays a greater role than chromaticity (Yantis & Jonides, 1996). Therefore, the onset of luminance in the boxes is equally effective for CDs as for CNs, because CDs and CNs perceive luminance about the same. The readability of the black text on a red background is "NE" for CDs. The text readability of other text and background color combinations for CDs is equivalent to that for CNs.

Site Information Display

Site Information Display presents a table of airport weather situations. Airport codes are listed in the leftmost column. Other columns list operational mode, alert, and storm information. Each row is for one airport. The text background of airport codes is color-coded to represent the operational status of weather sensors: yellow for storm cells, red for action alert, blue for operational, and black for not-operational. The text of airport codes is white on a red, blue, or black background, and black on a yellow background. Without color, users are able to infer the status of airport weather by reading the text in other columns. Thus, the colors have an inference redundant cue.

Red, yellow, and blue for identification

These colors are used to identify the weather status of airports, with texts in other columns serving as the inference redundant cue. Theoretically, the redundant text is less effective than colors. However, since the whole ITWS system uses many sets of color codes for identification, the effectiveness of colors in identification is greatly reduced in general. In real operations, users tend not to use color as the primary cue when there are too many colors in a display. Therefore, the effectiveness of color could be the same for CDs and CNs, because color is no longer a primary cue to acquire information. However, the chromaticity difference between red and yellow for CDs is below the identification threshold, so red and yellow are "NE." The text readability for CDs is equivalent to that for CNs.

Statistics

In this section, we present the results in Tables 1-6 graphically to provide an overall description of the effect of CDs in using ATC displays.

Figure 1 shows the overall effect of color use across the three primary displays: ACD, STARS, and DSR. The left panel shows the effectiveness of color for attention and identification tasks. The right panel shows

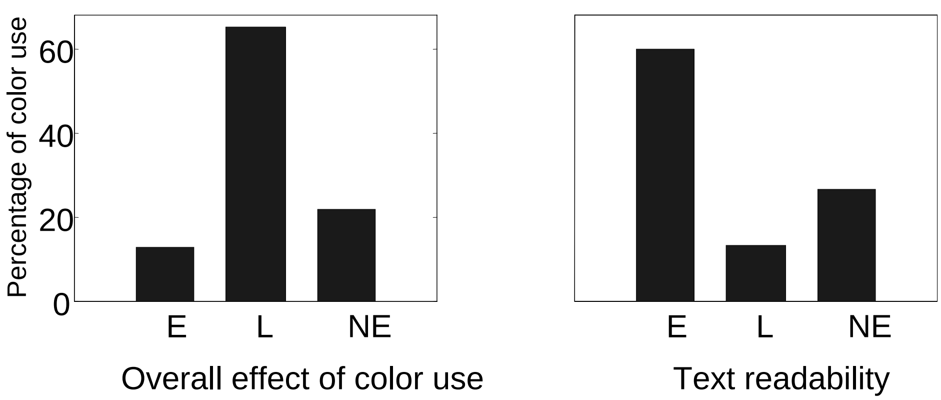

Figure 1. The statistic effect of color use for CDs relative to CNs in the three primary ATC displays: DSR, ACD, and STARS. The left panel shows the overall effect of color use for CDs relative to CNs in attention and identification tasks. The horizontal axis represents the three categories of color-use effectiveness: "E" for equivalent effective in CDs and CNs, "L" for less effective in CDs, and "NE" for not effective in CDs. The vertical axis represents the percentage of color usages in each category, calculated as the number of color usages in a given category divided by the total number of color usages for attention and identification. The right panel shows the effect of color use on text reading. The horizontal axis indicates the three categories of text readability for CDs relative to CNs: E, L, and NE. The vertical axis is the percentage of colored text in each category.

text readability associated with color use. In each panel, three categories of effectiveness, "E," "L," and "NE" are listed along the horizontal axis. The vertical axis is the percentage of occurrence in each category, calculated as the number of occurrences in a given category divided by the total number of times that color is used for attention and identification or text reading.

Notice that about 10% of color usages belong to the "E" category, meaning that CDs can use color-coded information as effectively as CNs in those applications. More intriguingly, about 22% of color uses belong to "NE," indicating that in these situations CDs might not be able to effectively use color-coded information in these ATC displays. Since the primary displays are critical for controlling traffic, this percentage may be high enough to represent a potential safety concern. Further task analysis and experimental validation needs to be performed regarding the 22% in the NE category for color usages to elucidate the operational effects of color use on ATC task performance. The right panel shows that about 30% of color usages in text result in less-than-threshold text readability, suggesting that CDs may encounter some difficulty in reading text associated with color use.

Figure 2 is in the same format as Figure 1, showing the data for the three supporting displays: URET, TMA, and ITWS. Compared with the results in Figure 1, about 50% of color usages for attention and identification belong in the "NE" category. The right panel of Figure 2 indicates that 35% of color usages in text could result in text reading problems. These cases also require further investigation.

Figure 3 shows the effect of redundant cues across the three primary displays, DSR, ACD, and STARS. The horizontal axis is comprised of the four categories of effectiveness of redundant cues relative to color. The category "NA" denotes color usages where no redundant cues are applied in addition to color. There are several cases in which the effect is uncertain, depending on individual situations. For example, if a filled orange-red area for heavy weather were significantly larger than the area of a datablock, then shape would be as effective as color in capturing attention. However, if the area is less than that of a datablock, then its capacity to attract attention is limited. In such cases, we used the lowest possible scale for the graph, e.g., the effect is the orange-red in attention is "L" as Figure 3 is concerned.

The results in Figure 3 are intriguing. While most color use guidelines emphasize the importance of redundant cues, about 20% of color usages for attention and identification tasks belong to the "NA" category, meaning that colors were used without redundant cues. Moreover, even when redundant cues are used, in most cases the effect of the cue is either less than the effect of color, or it is not effective for the given task purposes. Among all the color usages for attention and identification, only about 8% have redundant cues that are as effective as colors.

Figure 4 shows the effect of redundant cues in the three supporting displays, TMA, URET, and ITWS. The figure is in the same format as that of Figure 3. The percentages of the "E" and "NE" categories are similar to those in the primary displays. However, the percentage of the "NA" category is much higher – 46% of color usages for attention and identification in the supporting displays do not have redundant cues. This high percentage would seem to imply that the human factors effort in the interface designs of supporting displays was inadequate.

CONCLUSIONS AND DISCUSSION

In this report, we analyzed the effect of color use in ATC displays on CDs. The analysis was performed for three primary displays: DSR, ACD, and STARS, and three supporting displays: URET, TMA, and ITWS. For each display, we first identified the situations where color was used as a primary cue for attention or identification tasks. For those situations, we identified achromatic redundant cues (if any) and assessed their effectiveness relative to colors. We then applied the algorithms developed in our previous report (Xing & Shcroeder, 2005b) to compute the effectiveness of color for CDs relative to CNs. Finally, if color was used in texts, we computed and compared the text readability for CNs and CDs. These three values gave an overall description of how color vision deficiencies might affect the use of color displays.

The Effect of Redundant Cues

We often hear the argument that CDs can use redundant cues to perform color-related tasks. However, our analysis showed that redundant cues should be chosen carefully to fit the task purpose. Otherwise, the cues could be either less effective than colors or not effective at all. For example, if a controller needs to devote immediate attention to a target, then the redundant cue should be flashing or having a luminance much greater than other materials displayed in the area. Text and shapes are not effective for this purpose. Also, if a controller needs to identify different types of information, then the redundant cues should be visually distinctive from each other and should be reliably named. A good example of redundant cues for identification is the use of distinctive shapes in ITWS, such as lines and circles to identify severe weather in addition to colors. An opposite example is using text as a redundant cue for identification. Visual experiments have demonstrated that text is less effective than colors for identification in complex scenes (Christ, 1975).

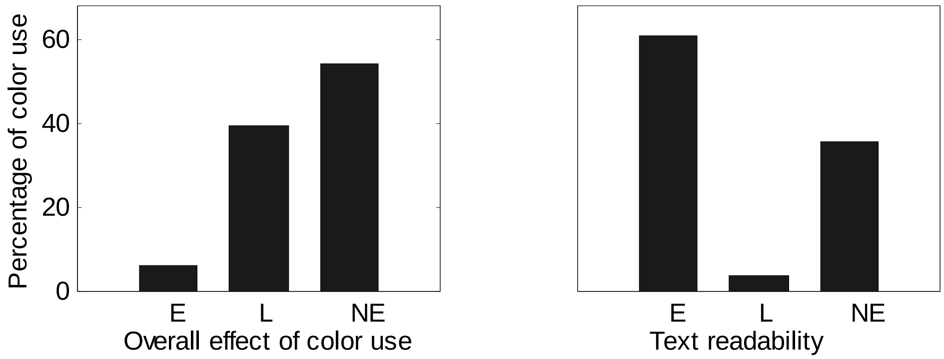

Figure 2. The statistic effect of color use for CDs relative to CNs in the three supporting ATC displays (URET, TMA, and ITWS). The format of the figure is the same as that of Fig. 1.

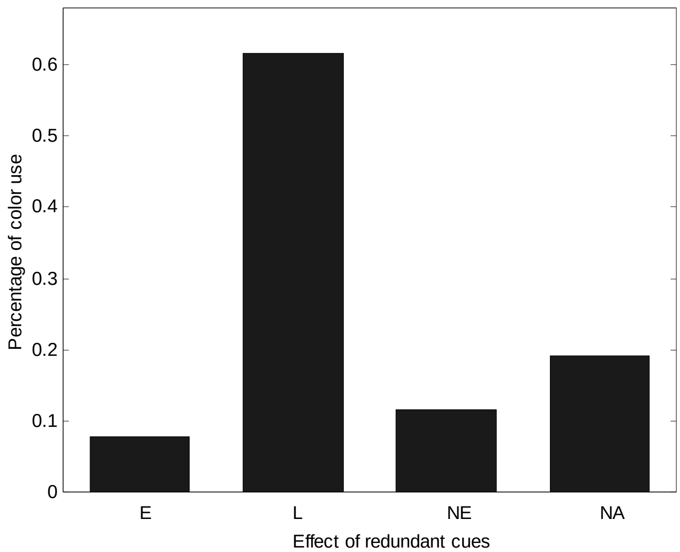

Figure 3. The effect of redundant cues relative to colors for color usages in the three primary ATC displays (ACD, STARS, and DSR). The analysis was performed only on the color usages with a task purpose of attention or identification. The horizontal axis indicates the categories of the effectiveness of redundant cues relative to colors, with “E” for equivalent, “L” for less effective, and “NE” for not effective for CDs. In addition, the “NA” category is denoted to the situations where color is used for attention or identification without redundant cues.

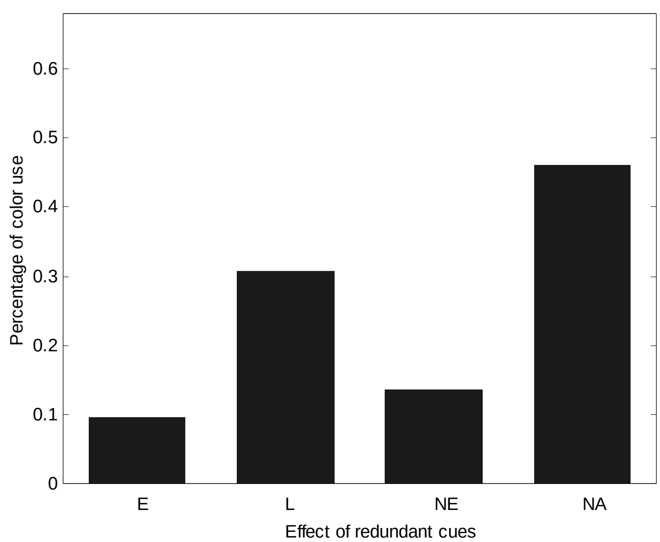

Figure 4. The effect of redundant cues relative to colors for color usages in the three supporting displays (URET, TMA, and ITWS).

Text Readability

Through the analysis, we noticed that there were many cases where text readability could be a potential problem for CDs. In fact, we reported only a portion of the cases used in ATC displays. We calculated the text readability for those situations where color was used for attention or identification. In ATC displays, color is also widely used to segment texts from other materials. Moreover, color is often applied to texts without an apparent underlying rationale. In those situations, while color should not affect CDs' task performance because it does not have any meaning, it can introduce low text readability. Given that a large portion of ATC tasks involves text reading, any new color vision standard should take this factor into consideration.

Limitations of the Analysis

Finally, we need to point out that the analysis in this report only provides a baseline assessment of the effect of color vision deficiencies. One limitation in our analysis is the effects of color vision deficiencies. The algorithms we used are based on those developed by Brettel et al. (1997). It simulates severe color vision deficiencies, in which one or two types of cones are completely absent from retinas. Many individuals have mild color vision deficiencies, in which the number of a certain type of cones is less than normal, or the cones are less sensitive than normal. So, the effects we estimated may differ, depending on the extent of the color vision deficiency. Another limitation is the lack of operational considerations. Since there is a high redundancy in aviation, controllers may use other sources to acquire color-coded information. Therefore, while there are a number of cases in Tables 1-6 where color use has the potential to negatively affect task performance of CDs, in real operations color may or may not cause problems for CD controllers, depending on individual situations and other redundancies in the ATC system. The purpose of this report is to narrow the range of situations where color use has the potential to cause problems for color-deficient controllers. A further step is to conduct a task analysis to determine how critical it is for controllers to be able to use color-coded information, and determine whether controllers have other ways to get around color vision deficiencies.

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