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Reexamination of Color Vision Standards, Part I: Status of Color Use in ATC Displays and Demography of Color-Deficit Controllers

Jing Xing
David Schroeder

Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

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16. Abstract

This report describes the status of color use in current air traffic control (ATC) displays. It represents the first step in our effort to reexamine the color vision standards for air traffic controllers. The current job-related color vision tests used by the FAA are based on an analysis of ATC tasks conducted in the 1980s. Over the past decade, many color displays have been introduced while the job-related screening tests for applicants are based on the earlier data. Thus, it is necessary to reexamine the current color vision standards. We first performed a demographic study to identify the number of controllers in the current ATC workforce with color vision deficiencies. The results indicated that there are 152 color-deficient controllers in eight of the nine FAA regions across the country. To understand how colors are being used in ATC displays and how they may affect the job performance of color-deficient controllers, we collected and analyzed information about color displays from nine ATC facilities, including three air traffic control towers, three TRACONs, and three en route centers. The main findings are summarized as follows: 1) All the basic colors and some non-basic colors are being used in ATC displays; 2) Critical information typically involves the use of red or yellow colors; 3) Colors are used mainly for three purposes: drawing attention, identifying information, and organizing information. Yet, none of the colors is used exclusively for a single purpose across facilities. The results raise questions regarding the adequacy of the current job-related color vision tests, given today's task requirements. We also discuss several possible solutions to bridge the discrepancies between the current color vision standards and the extensive use of color displays.

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LIST OF ACRONYMS USED IN THIS REPORT

ACD . . . . Color ARTS Display
AMASS . . . . . . Airport Movement Area Safety System
ARTS. . . . . Automated Radar Terminal System
ATC. . . . . Air Traffic Control
ATOP . . . . Advanced Technology and Oceanic Procedure
CIWS. . . . . Corridor Integrated Weather System
CRD . . . . Computer Read-out Device
DBRITE . . . . . Digital Bright Radar Indicator Tower Equipment
DSP . . . . Departure Spacing Program
DSR. . . . . Display System Replacement
ETMS . . . . Enhanced Traffic Management System
FAA . . . . Federal Aviation Administration
IDS . . . . Information Display System
ITWS. . . . . Integrated Terminal Weather System
PRM . . . . Parallel-Runway-Monitor
RDVS . . . . Rapid Deployment Voice Switch
STARS . . . . Standard Terminal Automation Replacement System
TDW. . . . . Tower Display Workstation
TDWR . . . . . . Terminal Doppler Weather Radar
TMA . . . . Traffic Management Advisor
TRACON . . . . Terminal Radar Approach Control
URET . . . . User Request Evaluation Tool
VSCS. . . . . Voice Switching Communication System
WSP. . . . . Weather and Radar Processor

Reexamination of Color Vision Standards I: Status of Color Use in ATC Displays and Demography of Color-Deficit Controllers

INTRODUCTION

Color deficiency is denoted to people who have deficits in color perception, with eight to ten percent of the male population experiencing some degree of a color vision deficiency. Given that certain job tasks require controllers to discriminate colors, the FAA established color vision standards to screen air traffic controller applicants. The existing standards evolved many years ago when the primary color-related tasks of controllers involved (a) the identification of red and black text on flight progress strips, and (b) the identification of red, green, and white signal lights used at airports (Mertens, 1990; Milburn, 2004). However, during the past decade, there has been a significant increase in the use of colors in ATC displays. Walking into any ATC facility, one can see a number of color displays. Moreover, paper strips are being replaced as the User Request Evaluation Tool (URET) is introduced in en route facilities. In fact, advanced computer displays have become an important source for en route and Terminal Radar Approach Control (TRACON) controllers to acquire information. In larger airport control towers, while controllers constantly scan the airport runways, look for approaching aircraft, and listen to pilots and other controllers, they still use several electronic displays to acquire information such as departure and arrival sequences, weather, and runway situations. Hence, it is necessary to reexamine the color vision standards and make sure that the standards fit current job requirements.

The nature of color use in ATC displays is complicated by differences in the use of colors across manufacturers and across ATC facilities. The rapid development of display technologies has made it simple to put colors on computer monitors. On the other hand, there are no standards or requirements about how manufacturers should use colors. Therefore, various color schemes have been used in current ATC displays. Some displays even allow users to define their own color schemes. As a result, the colors used in the same automation display can vary across facilities.

As the first step of our effort to reexamine color vision standards, we documented color vision standards, examined the demographics of color-deficient controllers, and collected information about color use from nine ATC facilities. We then analyzed the data and presented the results with respect to three types of ATC facilities: air traffic control towers, TRACON, and en route traffic control centers. Finally, we discuss the discrepancies between color use in ATC displays and current color vision standards for controllers.

METHODS

We made site observations on color use in displays at nine ATC facilities: three air traffic control towers, three TRACONs, and three en route centers. Seven facilities were in the Eastern Region and two in the Western Pacific Region. The facilities range from medium to large. In June 2004, the three towers we observed were ranked as 13th, 32nd, and 49th busiest; the three TRACONs were ranked as 2nd, 4th, and 15th busiest; and the three centers were ranked as 4th, 6th, and 18th in ATC activities. Two of the centers control both inland and oceanic air traffic.

At each of these ATC facilities, we performed the following activities: 1) learned how controllers used computer displays through briefings provided by facility managers, supervisors, and technical staff; 2) observed how controllers used color information to perform tasks; and 3) recorded the colors used in displays and their relevance to task performance. In addition, we also discussed with the facility staff a number of color issues such as advantages and drawbacks of using colors in displays, the potential effect of color vision deficits on task performance, etc. A list of the questions we used is in the Appendix of this report.

We used a digital camera to take screen shots of the displays. Those pictures were included as part of our documentation of color use in current ATC displays. The pictures were also used in our analysis of the potential effects of color vision deficiencies on ATC task performance.

We analyzed the data with respect to the three types of ATC facilities. For each type of facility, we examined three issues of color use: 1) The colors being used; 2) the frequency of use; and 3) the purposes. The answers to these questions provide descriptions of color usage by controllers and the rationale of necessaries to revise existing color vision standards.

RESULTS

I. Current color vision standards and demography of color-deficient controllers

Current color vision standards

In 1978, the FAA began to use clinical color vision tests to screen applicants for air traffic control specialist positions. The clinical color vision tests used by the FAA included the Pseudoisochromatic plates (such as Dvorine and Ishihara) and the Farnsworth Lantern test. The FAA initially required controllers to take annually recurring color vision tests. This requirement was removed in 1996. As the result, a controller is qualified for color vision throughout the service period once passing the screening test at hiring.

Beginning in 1992, the FAA applied two job-related color vision tests to screen air traffic control specialist applicants. Mertens and his colleagues developed these practical tests (Mertens et al., 1992; 1995). For en route controllers, the practical test involved identifying the colors of black and red text written on flight progress strips. For tower controllers, the test was to identify the colors of red, green, and white presented on aviation lanterns that mimicked the signal lights used in airports to control aircraft. If an applicant failed clinical color vision tests but passed job-related tests, the applicant was deemed qualified. Mertens et al. (1990) found that about 10% of the subjects who failed clinical tests could pass the job-related tests. As a result, a certain percentage of controllers with mild to moderate color vision deficits were able to enter the job. The practical test ensured that they would successfully handle the color-related tasks in the operational environment.

Demographics of color-deficient controllers

We searched the FAA medical Covered Position Decision Support System (CPDSS) database for information about color-deficient controllers in the current workforce. The data were subsequently confirmed by regional flight surgeons. As of August 2004, there were 125 color-deficient controllers in eight of the nine FAA regions across the country. There were no color-deficient controllers identified in the Alaskan region. Table 1 illustrates the distribution of color-deficient controllers in the nine FAA regions. Considering that there are more than 16,000 U. S. controllers, the percentage (less than 1%) of color-deficient controllers in the current workforce is very low.

II. Status of color use in ATC displays

En route traffic control centers

ATC displays can be classified into three categories according to their functionality. Primary displays, also called situation displays, are the ones with which operational controllers monitor moment-to-moment traffic and to observe changes in aircraft altitude, direction, and speed as instructions are issued to maintain separation. Secondary displays are the part of a workstation that controllers use to acquire additional information to support their decision-making and coordination of the flow of air traffic. Advisory displays are located at non-operational control areas of a facility. Some advisory displays are placed on the walls of the operational control areas so that operational controllers can easily see the materials while seated at their workstations. The largest collection of these specialized displays is located in the traffic management section of the facility. Controllers within these areas are responsible for adjusting the volume of traffic entering the facility's airspace in light of existing weather conditions and staffing.

The primary display for en route controllers is a radar display called Display System Replacement (DSR) for inland air traffic or the OCEANIC for oceanic traffic. The secondary displays include soft-CRD (Computer Read-out Device) and Voice Switching Communication System (VSCS). Some centers also have a User Request Evaluation Tool (URET). The advisory displays include, but are not limited to, Enhanced Traffic Management System (ETMS), Traffic Management Advisor (TMA), and Corridor Integrated Weather System (CIWS). The advisory displays use many colors. Moreover, keyboards at the workstations and the Key Selection Device are also color-coded. ETMS allows individual users to customize its color palette. Thus ETMS was not included in the analysis of color use. The same is true for VSCS. In addition, since the OCEANIC display is being replaced by the Advanced Technology and Oceanic Procedure (ATOP), we did not analyze color data of OCEANIC. The data about ATOP were not available at the time of

Table 1. Numbers of color-deficient controllers in 9 FAA regions.

Region	ACE	AEA	AGL	ANE	ANM	ASO	ASW	AWP	AAL
Number	2	14	42	4	19	23	9	11	0

our facility observations. An initial look at the ATOP display suggests rather extensive use of color.

Colors used in displays. First, we wanted to know what colors are being used in the en route displays. Vision research has shown that eight chromatic colors are considered as basic colors (Boynton & Olson, 1987). Those include red, yellow, green, blue, orange, purple, pink, and brown. The basic colors can be reliably named and have exact equivalences across many languages and geographic regions. They segregate well because they are maximally separated in color space. Among the basic colors, red, green, yellow, and blue are called primary colors because they correspond to the color processing mechanism in the human visual system.

We listed the use of the eight basic colors in primary, secondary, and advisory displays in Table 2. In addition, the last column lists the usage of non-basic colors. A crossing symbol indicates that the color is used in at least one of the displays. Table 2 shows that nearly all the basic colors are used in the displays. In contrast, only a few non-basic colors are used. Typical non-basic colors include magenta, cyan, turquoise, and beige. Secondary and advisory displays use more colors than the primary displays. All of the primary colors are used in nearly all the display categories, with the exception of blue (blue is the DSR background color).

Frequencies of the colors being used. Next, we estimated how frequently the colors were used in the en route displays. The estimation was based on color-coding. For example, since URET used red twice in its Aircraft List, once in the Graphic Display window, and once in the Plan Display window, we counted that red was used four times in URET. The estimation also considered the luminance factor of colors. Again, taking URET as an example, in the Aircraft List red represented a conflict that was predicted to happen within the next five minutes, while a muted red (lower illumination) represented a conflict that was predicted to happen if the controller took other expected actions first. So, red was used twice here.

For each color category, the frequencies of its usage were summed across all the displays in the three centers. Figure 1 shows the histogram. The vertical axis represents the frequency with which a color was used in the en route displays. The horizontal axis represents individual colors, with red, green, yellow, blue, purple, orange, brown, pink, and non-basic colors, from left to right. Two bars are plotted for each color; the bar on the left is the total number of colors used across all the en route displays, and the bar on the right indicates the number of colors used in primary displays only. The results show that red, green, and yellow are used most frequently. This is especially true in the primary display. At present, the DSR display uses colors only for its graphic tool and weather information. Among the non-basic colors, cyan is used most frequently.

Notice that we treated the results in Figure 1 as estimates instead of accurate calculations. Two factors contributed to the estimation: 1) We did not observe some infrequently used windows of displays. For example, URET had seven windows but we observed that controllers only used three of them and rarely used the other four. Therefore, we did not collect data from those four windows. 2) There were other advisory displays that were not available in the three facilities we visited. Therefore, this analysis provided us with a qualitative, rather than a quantitative, description of how often colors were being used in en route facilities.

Purposes of color use. For each color we observed in the displays, we identified the purpose of its use. We found that colors were used for one of the three purposes: 1) Colors were used to draw attention. Because the basic colors are more salient than non-basic colors, they are often chosen to encode information that requires immediate attention, such as an alert or emergency. 2) Colors were used to identify certain types of information so that

Table 2. Colors used in en route displays.

	Red	Green	Yellow	Blue	Purple	Orange	Brown	Pink	Others
P	X	X	X				X	X	X
S	X	X	X	X	X		X		X
A	X	X	X	X	X	X	X		X

P = Primary displays
S = Secondary displays
A = Advisory displays

searching for the information in complex scenes could be completed more efficiently. In this case, each color has a distinctive meaning. For example, a controller may use a yellow outline to indicate a restricted flying zone on the DSR. The distance of an aircraft to that zone can then be displayed in yellow. The controller can identify the distance easily by searching for the yellow-colored text. 3) Colors are used to organize information by segmenting a complex scene into objects so that controllers can easily use displayed information. In this application, controllers do not have to remember the meaning of colors. Based on these observations, we can thereby classify the purposes of color use into three categories: *Attention, Identification,* and *Segmentation.*

Other than these three purposes, there are many situations where colors are used for no apparent reason. For example, we observed that some text was gray, dark green, blue, or another color. Those colors could be replaced by other colors without causing any operational difficulties for controllers who have normal color vision. However, the "no-purpose" has the potential to cause trouble for color-deficient controllers. For example, controllers who have deficits in perceiving red or green colors would have difficulties in reading green text written on a dark red background, because both green and red appear yellowish brown to them. It is desirable that a color should be used only where it has a functional purpose. Unfortunately, display manufacturers do not always follow this principle. Moreover, if controllers are allowed to set their own color palette, this could cause problems for them or their supervisors.

Here we use the Aircraft List of URET as an illustration of how the purposes of color use are determined. Figure 2 is a snapshot of the Aircraft List. The columns with the boxes on the left-most side of the window indicate flight status, encoded with red, muted red, yellow, muted yellow, cyan, and brown. In the first column, the boxes may turn into red or muted red. Red represents predicted loss of separation within less than five minutes. Muted red represents predicted loss of separation if the controller takes other expected actions first. Therefore, both red and muted red serve as alerts that require the immediate attention of controllers. In the second column, yellow means predicted conflict coming between 5-12 miles. Thus, yellow requires attention as well. While the yellow and red colors are to draw attention, each of them has different meanings, and controllers associate the color with its meaning. Therefore, we classified the purposes of these colors in both the *Attention* and *Identification* categories. The cyan color in the third column of boxes indicates aircraft on a conflict route. The brown color means that auto-prediction may not be available because of no tracking data for the aircraft. Unlike red and yellow, these two colors do not require controllers' immediate attention. Controllers only use the colors to identify relevant information. Thus, we classified the purposes of cyan and brown in the *Identification* category.

We identified the purposes of color use and summed the results across the en route displays. Figure 3 shows a histogram of color-use purposes. The upper, middle, and bottom panels correspond to *Attention*, *Identification,* and *Segmentation,* respectively. In each panel, the vertical

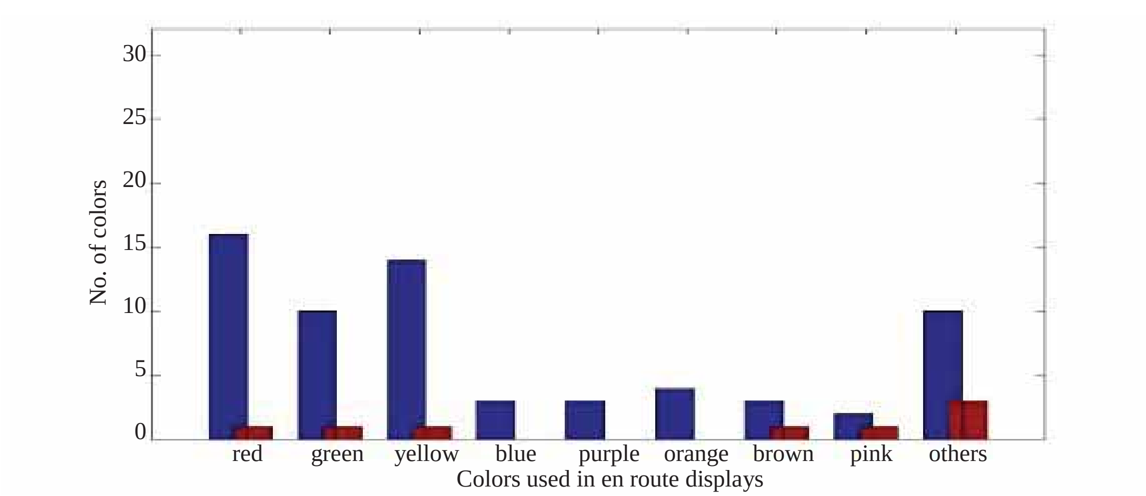

Figure 1. Frequency of color use in en route displays. The vertical axis represents the frequency of color use in the en route displays. The horizontal axis represents colors (red, green, yellow, blue, purple, orange, brown, pink, and non-basic colors, from left to right). Two bars are plotted for each color; the bar on the left is the total number of times a color is used across all displays, and the bar on the right indicates the number of times a color is used in primary displays only.

Figure 2. An example of the URET Flight Strip List display.

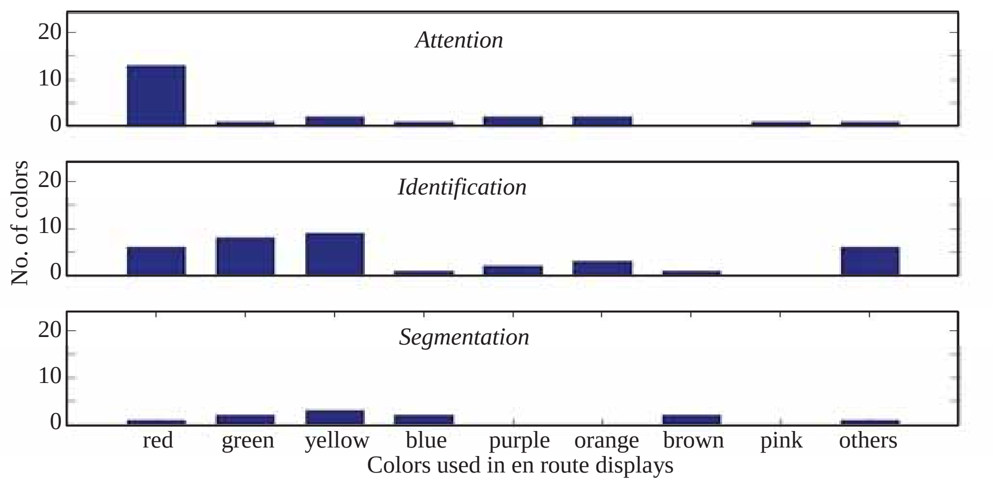

Figure 3: The purposes of color use in en route displays. The upper, middle, and bottom panels correspond to *Attention, Identification,* and *Segmentation,* respectively. In each panel, the vertical axis represents the frequency that a color is used for the given purpose. The horizontal axis represents the individual basic colors and non-basic colors as one category.

axis represents the frequency of a color used for the given purpose. The horizontal axis represents colors, with red, green, yellow, blue, purple, orange, brown, pink, and non-basic colors (from left to right). The results show that, while red is often used for *Attention*, it is also used for *Identification* and *Segmentation*. Ideally, red should not be used for non-critical purposes, because the colors used for *Attention* should not be used for *Segmentation* or "no-purpose." Many guidelines for color use in visual displays have recommended that red should be reserved only for the most important information. However, that is not the case with en route displays. Comparing the upper and bottom panels, we see that red, green, and yellow are more frequently used for *Identification* than other colors.

Notice that the results about color use in en route centers are based on the fact that URET is in use in these facilities. We need to point out that only a limited number of en route facilities currently use URET. For those centers not using URET, the use of color in secondary displays is not as extensive as presented in this section.

TRACON

Operational controllers in a TRACON work with their primary displays to maintain separation between aircraft. They also frequently use secondary displays to acquire information and communicate with others. In addition to the operational control positions, each facility usually has some positions for supervisors and special designated controllers. For example, a TRACON may have several controllers assigned to the positions where the display is a Parallel-Runway-Monitor (PRM) tool. There are other advisory displays from which operational controllers acquire information, such as weather displays. The advisory displays vary from facility to facility. The primary display in the TRACON environment used to be the Automated Radar Terminal System (ARTS) or Common-ARTS. Now they are being replaced with a Color ARTS Display (ACD) or Standard Terminal Automation Replacement System (STARS). The secondary displays include Information Display System (IDS),t or ACE-IDS, and the communication system called Rapid Deployment Voice Switch (RDVS). Advisory displays include ETMS, ITWS, PRM, and DSP (Departure-Spacing-Program). These displays are all color-coded. As mentioned earlier, ETMS is not counted in the following analysis. We also did not include RDVS in the analysis. While RDVS used colors, information is precisely encoded by locations, so controllers primarily use location cues to acquire information and they ignore colors.

Colors used in TRACON displays. Table 3 lists the use of eight basic colors and other non-basic colors in primary, secondary, and advisory displays; in the same format that was used in Table 2. The result shows that all the basic colors but pink are being used in TRACON displays. The non-basic colors include magenta, cyan, turquoise, beige, and others. Advisory displays use more colors than primary and secondary displays. The four primary colors are used in all display categories. Thus, TRACON controllers should be able to recognize at least those four colors.

Frequencies of the colors being used. For every color category, the frequency of its usage is summed across the displays in the three TRACONs. Figure 4 shows a histogram, with the same format as that of Figure 1. The vertical axis represents the frequency of color use, and the horizontal axis represents individual colors. The bars on the left show the color usage for all the TRACON displays; and the ones on the right indicate the number of times a color is used in the primary displays only. The results indicate that red, green, and yellow are the most frequently used colors. Compared with the data for en route displays (Figure 1), TRACON displays use colors more extensively. Another difference between TRACON and en route displays is that the primary TRACON displays use many non-basic colors, most of them associated with the STARS system.

Purposes of color use in TRACON displays. We identified the purposes of color use for TRACON displays and summed the results by colors and purposes. Figure 5 shows the histograms of color-use purposes, with the same format as that of Figure 2. The upper, middle, and bottom panels correspond to *Attention*, *Identification,* and *Segmentation,* respectively. The vertical axis represents the frequency of a color used for the given purpose, and the horizontal axis represents colors. Figure 5 indicates that, while red is used a majority of the time for *Attention*, it

Table 3. Colors used in TRACON displays.

	Red	Green	Yellow	Blue	Purple	Orange	Brown	Pink	Others
P	X	X	X	X		X			X
S	X	X	X	X					X
A	X	X	X	X	X	X	X		X

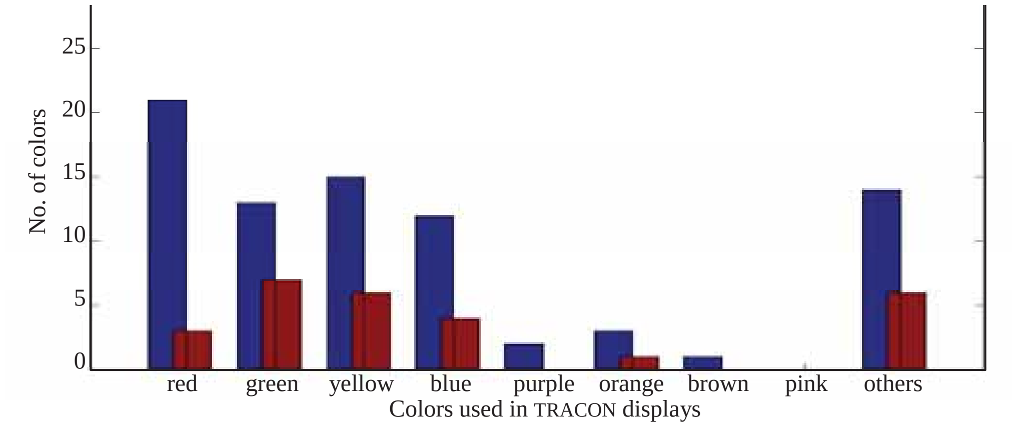

Figure 4. Frequency of color use in TRACON displays (in the same format as Fig. 1).

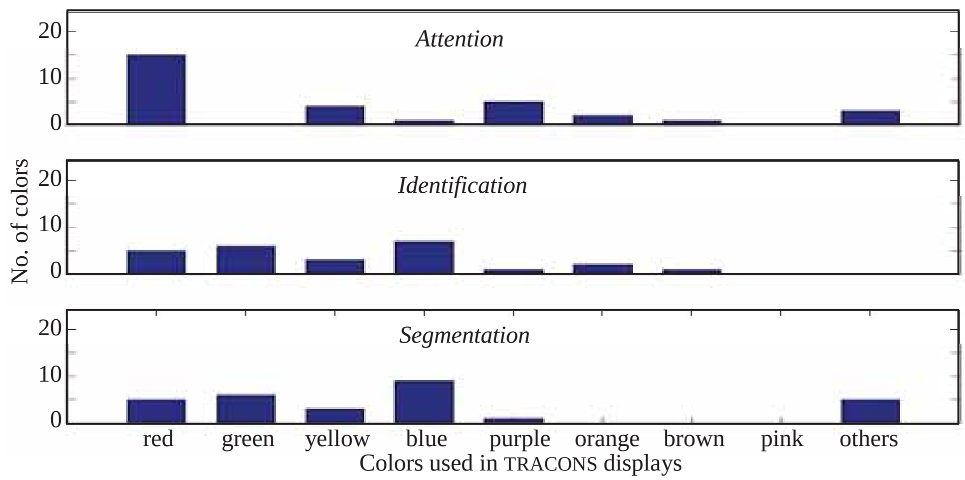

Figure 5: The purposes of color use in TRACON displays (in the same format as Fig. 3).

is also used for *Identification* and *Segmentation*. On the other hand, many other colors are also used for *Attention*. Thus, it is difficult for a controller to associate specific colors with critical information. This problem could become more severe for color-deficient controllers. These color schemes imply that controllers should be able to distinguish all the basic colors and some non-basic colors to use the displays as assumed by manufacturers. In addition, TRACON displays use colors frequently for *Segmentation* and "no-purpose," further complicating controllers' mental association of color meanings.

Tower

Tower controllers do not use radar displays to control aircraft, and there is no primary tower radar display, by definition. However, they do use displays to acquire information. The secondary displays used in towers are Tower Display Workstation (TDW) and R-ACD. TDW is the modified tower version of STARS, and R-ACD is ACD modified for daylight illumination. An equally important display in towers is the airport movement surveillance system, either Airport Movement Area Safety System (AMASS) or Digital Bright Radar Indicator Tower Equipment (DBRITE). The advisory tools vary greatly across towers. Those include Information Display System (IDS), Weather and Radar Processor (WSP), Integrated Terminal Weather System (ITWS), Terminal Doppler Weather Radar (TDWR), Departure Spacing Program (DSP), and Landing Panel that displays status of airport surface lights.

Colors used in tower displays. Table 4 lists the colors and their use in secondary and advisory displays. The results are similar to those of TRACONs because many displays used in TRACONS are also present in towers with slight modifications. For example, a tower uses

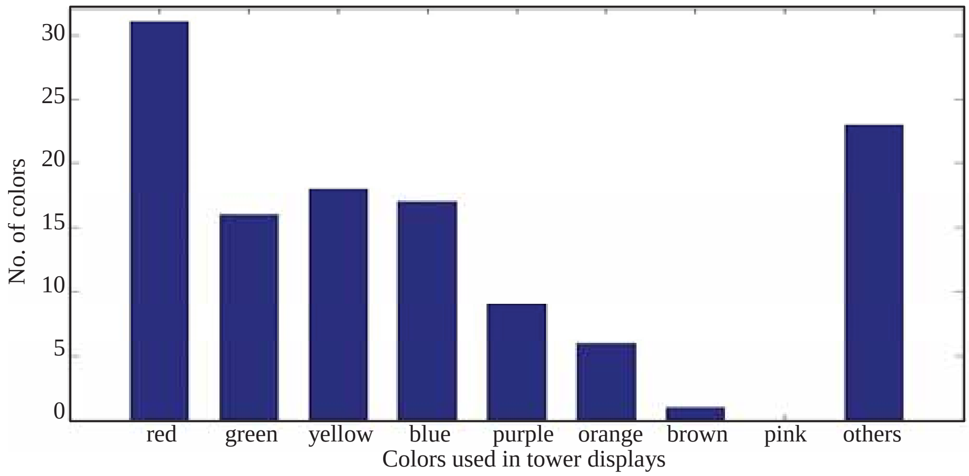

Figure 6: The frequency of color use in Tower displays. The figure is in the same format as that of Figure 1.

R-ACD if the associated TRACON uses ACD; a tower uses TDW if the TRACON uses STARS. R-ACD has two versions of color schemes, one for daylight and the other for nighttime. However, most controllers prefer to use the nighttime version, even in the daytime, because they like the color scheme of the daytime version better.

Frequencies of the colors used in tower displays. We estimated the frequencies of each color used in tower displays. Figure 6 shows a histogram of color use. The vertical axis represents the frequency of a given color used in the displays; the horizontal axis represents individual colors arranged in the same order as that in Figure 1. Figure 6 indicates that all the basic colors, except pink, are used in tower displays. Moreover, compared with TRACONs and Centers, towers use a number of non-basic colors. As a result, there are many color schemes in tower displays, and the schemes may be confusing. Essentially, we can say that many colors are equally important in the tower environment due to the current inconsistent color schemes.

While many people have the impression that towers do not use many colors, surprisingly, Figure 6 indicates that towers use colors more frequently than TRACONs and en route centers do. One of the reasons for the extensive color use is to display weather information. Towers have a large variety of weather displays. Many colors are used to encode different levels of precipitation and wind speed.

Purposes of color use in tower displays. Figure 7 shows the histogram of color-use purposes. The upper, middle and bottom panels correspond to *Attention*, *Identification,* and *Segmentation*. The vertical axis represents the frequency with which a color is used for a given purpose, and the horizontal axis represents colors. Figure 7 indicates that most basic colors (other than green and pink) and many non-basic colors are used for *Attention*. Therefore, controllers cannot rely on a single color to distinguish critical from non-critical information. All the basic colors except pink are used for *Identification*. Among the non-basic colors, cyan and magenta are most frequently used for *Identification*. These two colors are equally effective as the basic colors in target searching (Smallman & Boynton, 1990). Notice that in the bottom panel, the four primary colors are dominantly used for *Segmentation*, which introduces potential confusion with the *Attention* color schemes. For example, the color red could mean a wind shear warning, yet it could also mean nothing special such as an aircraft destination. In these situations, controllers have to use other visual features to identify critical information.

While we presented the use of color in tower displays in this section, computer displays only comprise part of the information resources for tower controllers. The ATC tasks in control towers include identifying aircraft movement through the red, green, white, and blue lights at night or during low-visibility conditions. Controllers also need to distinguish between aircraft based on logos/colors. Taking those situations into consideration, the actual use of color by tower controllers is more extensive than what was reported in this section.

III. Experiences and preferences in color use

At each facility, we discussed a number of color issues with the facility staff including controllers, supervisors, managers, technical support engineers, and quality

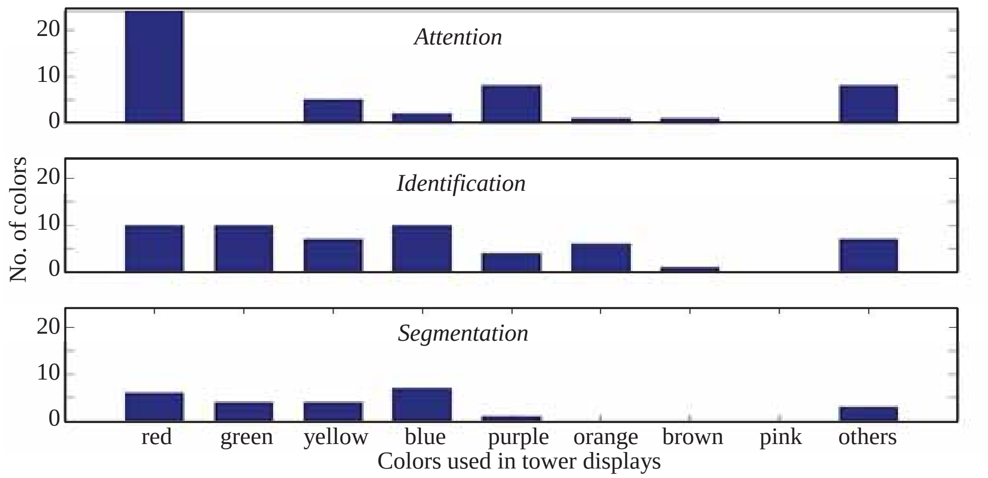

Figure 7: The purpose of color use in tower displays (in the same format as Fig. 3).

assurance analysts. While we did not systematically collect data from them, through discussions we acquired information about their experiences and preferences with color use. Next are some issues in which we received consistent opinions from the facility staff.

1) History of color use

Except for the new Potomac TRACON, most facilities have about ten years of experience with using some color displays. In particular, there has been a substantial increase of color use in primary displays during recent years. At terminal facilities, monochromatic ARTS displays are being replaced with ACD and STARS. At en route facilities, DSR has adopted moderate color-coding and will use more colors in the datablocks. URET has been deployed at several en route centers in recent years and will continue to be deployed.

2) Reaction to color use

The overall reaction to color use is positive. Controllers and supervisors like color-coding because it saves time and sometimes makes their tasks easier. On the other hand, they acknowledged that color-coding was not necessary in many situations, and they could not take advantage of some color-coding.

3) Operational errors associated with color use

None of the staff we talked with was aware of any operational error specifically associated with a controller's color vision deficiency. However, some facilities did report operational errors associated with color-coding. For example, in two TRACON facilities, ARTS Color Displays used different colors to represent controllers' own and unowned aircraft. This scheme, by focusing controllers' attention on own versus unowned aircraft, could cause loss of aircraft separation in certain circumstances. Informal analysis at one facility suggested that about one-third of their operational errors might be related to such color use.

4) Text readability

All of the staff members agreed that good text readability was crucial for controllers. Text should be read quickly in an error-free manner. Low text readability was unacceptable for effective task performance. However, we observed a number of situations where highlighting text with colors resulted in lowered text readability.

5) Effect of color deficiencies

Until very recently, most staff members were not aware that color deficiencies could potentially affect task performance associated with using color displays. After we explained how color displays might appear to a color-deficient viewer, about half of the staff agreed that color deficiencies could have a negative effect on task performance. Others thought that color-deficient controllers could use redundant cues to get around the problem.

6) Complaints about color use

One of the major complaints about color use was using red to encode warning or alert messages. Red-colored messages in ATC displays are often not conspicuous enough for immediate detection. To effectively draw attention, a target has to be brighter than other materials on a display. However, red is dimmer than many other colors such as white and green in ATC displays. Several staff members at different facilities expressed the same opinion: "Don't use red for alert unless the red symbol is very bright."

7) Color palette customization

Nearly all of the facility staff were against color palette customization by individual controllers. The common opinion was that color schemes should be consistent across the ATC system, especially when a display is used to control aircraft (i.e., the primary displays).

Since none of the staff members we talked with had any experience in working with color-deficient controllers, we could not obtain direct information about the effects of color deficiencies on ATC task performance. However, some of the opinions above provided a hint. For example, many of the staff members complained about low visual conspicuity of red warning messages. When viewed by color-deficient controllers, such red signs would appear dark yellowish with a reduced luminance, thus the conspicuity would be even lower compared to that when viewed by color-normal controllers. Unless the red signs are accompanied with a flashing cue, the detection of such critical information would be impaired in color deficient controllers.

DISCUSSION

Our facility observations confirmed that color displays have become a major source for controllers to acquire information. However, the current job-related color vision tests are based on the use of flight progress strips and signal lights. The traditional paper strips are rapidly being replaced by electronic displays at en route centers. Therefore, the strip-based test is no longer sufficient for today's ATC tasks. Also, given the use of color in tower displays, the job-related color vision test based on the discrimination of red, green, and white lights in the modified Farnsworth Lanterns alone may not adequately fulfill the color-related task needs for tower controllers. We observed that tower controllers acquire information from many color displays. Given these discrepancies between the color vision tests and the nature of present ATC tasks, it is necessary to reexamine the current color vision requirements and make sure that they fit the current task requirements. The reexamination effort shall focus on the criticality of color use, whether a color usage is associated with achromatic redundant cues, and relationships of color use with task performance.

Given the diversity of color use in ATC displays, to develop new job-related color vision tests will require extensive research. The effort must include reviewing existing displays, identifying instances where color may be used as a non-redundant cue, assessing the criticality of information to safe flight, and assessing whether the performance of controllers with color vision deficits differs significantly from that of color-normal controllers. Based on the results of the above effort, we must then identify the practical tests that can be used to ensure that applicants who enter the profession possess adequate color vision to safely and efficiently carry out their duties.

In this phase of the report, several alternatives to new, possibly more restricted, color vision tests are proposed. Next, we discuss the feasibility of those approaches.

1) *Instead of creating new job-related tests, is it possible to solve the color deficiency problem through manufacturers' effort?*

Theoretically, this might be done but it is not practical. For example, the UK Civil Aviation Authority recommended that the chromaticity differences between the colors in a display should be checked with the perceptually uniform color space to make sure that colors can be discriminated by human eyes. This method can be extended to the domain of color deficiencies, i.e., the colors in a display should be checked against the color discrimination differences of color-deficient individuals. This procedure can ensure that all selected colors are distinguishable by color deficient personnel. However, the drawback of this strategy is that it greatly limits the use of color and decreases the efficiency of color-coding. In addition, it can introduce further inconsistency of color schemes used in existing and future displays.

2) *Is it possible to solve the color deficiency problem by giving controllers the flexibility of using colors of their own preference?*

We observed the application of this strategy in ETMS. Indeed, this strategy might greatly relieve the color deficiency problem. However, this strategy has some considerable drawbacks: 1) It causes coordination problems for controller supervisors. Inconsistencies in color use among controllers may confuse a supervisor's understanding of a situation and thus interfere with his or her decision-making. 2) Inconsistencies in color schemes may cause coordination problems between controllers.

When working as a team, a controller could be required to work on a display that uses a different color scheme from the one that he normally uses. Moreover, imagine that a color-deficient controller needs to work on a display that was customized by a controller with normal color vision. 3) Some controllers may overuse this flexibility. They are probably not aware of some principles of using colors in ATC displays. For example, we observed several cases where red was used for unimportant background information such as boundaries. That is contrary to the general design principle that red should be reserved for critical information only. Furthermore, some people tend to apply too many (more than ten) colors to a single display mode, while the human brain cannot effectively search for a particular color when there are more than six or seven (Carter & Cahill, 1979).

3) *Can the color deficiency problem be avoided by always having redundant cues?*

The answer to this question depends on whether colors are used as primary visual cues for critical information. Primary visual cues are the most perceptually conspicuous features of an object. The human visual system uses primary cues to detect critical information without a searching effort. Brightness and blinking/flashing are the top choices of primary cues for visual perception. While color is also visually conspicuous, color scientists do not recommend using color as the primary cue to draw attention because of color deficiency concerns. Moreover, the appearance of displayed colors can vary with changes in the display environment and monitors. For instance, colors with the same specifications can appear different across monitors. Even for the same LCD monitor, color appearance can change greatly when viewed from different angles. Mertens (1990) suggested that color should never be used for the purpose of attracting attention. Unfortunately, we observed many situations where colors were used as the primary cue to capture attention in ATC displays.

The argument here is whether the color deficiency problem can be solved by always using redundant cues. Theoretically, color-deficient controllers can use redundant cues such as luminance, text, shape, or texture to back up their color perception. However, information in most ATC displays is highly dynamic and complex, yet most ATC tasks have to be performed in a timely and efficient manner. For instance, a controller often needs to find a piece of information in a complex display containing multiple pieces of information during busy traffic. This has to be done accurately and quickly. The purpose of using color in ATC displays is to reduce the time needed to identify important information. For example, a warning message in a bright red color can be perceived by color-normal controllers instantly. However, the message would appear dark yellowish to some color-deficient viewers and thereby reduce the conspicuity required to capture attention (Brettel, Vienot, & Mollon, 1997). While the viewers can still identify the message by serially searching redundant cues such as texts or shapes, it takes longer to find the message (Christ, 1975; Treisman & Gelade, 1980). Thus, having redundant cues may not always be sufficient for rapidly evolving ATC tasks. Redundant cues can be used to avoid the color deficiency problem only when they are perceptually conspicuous and can be perceived "at-a-glance."

CONCLUSIONS

In this report, we analyzed the current color use in ATC displays. The main findings are summarized as follows: 1) All the basic colors (red, green, yellow, blue, orange, purple, pink, brown) and many non-basic colors are being used in ATC displays. Color usage in the primary displays is more limited than in secondary and advisory displays; 2) Alert and emergent messages typically rely on red and yellow colors, but many other colors are also frequently used for critical information; 3) Colors are used mainly for three purposes: drawing attention, identifying information, and separating information, yet none of the colors is used exclusively for a single purpose across the displays. 4) In some situations, color usage has some potential to negatively influence performance. Overall, this study found that the use of color in ATC displays is more extensive than what was identified and used as the basis for the development of the current job-related color vision tests. The findings suggest that the existing job-related tests may not be sufficient for today's task requirements. Further effort is needed to bridge the discrepancies between the current color vision tests and the extensive use of color displays.

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APPENDIX A

List of Questions About Color Use in ATC Displays

The questions are organized into three categories: color experience, preference of color use, and observation of color equipments in facilities.

Experience:

1) How long have you had color-coded displays in this facility?

    What has been the general response?

        Positive features

        Negative features

2) Has there been any change in visual complaints (number or type)?

3) What, if any difficulties have controllers experienced in using the color-coded information? (e.g. misinterpreted the coding?)

4) As far as you know, do you have any controllers at the facility (in your work group) who have a color vision waiver?

5) If yes, have they experienced any difficulties in using the advanced color-coded displays? Nature of the problem?

6) Are there aspects of the color-coding or color symbology where color is the only way to identify a problem or concern?

(Are there enough redundant cues for color-coding on your display so that a color deficient controller can easily interpret the available information?)

7) If a color-deficit controller spends 0.5-5sec longer in noticing some color-coded information than a color-normal controller, what impact on overall task performance and safety would you expect?

8) Under what circumstances would misinterpretation of the color-coded information create a safety risk?

9) Have you personally experienced low text-readability due to color use, such as, white text on yellow background, blue text on black ground, etc.?

Have you observed other controllers experiencing difficulties?

10) Some colors on displays appear very dark such as dark blue or dark brown. Have you ever personally experienced any problems with legibility of text using these dark colors, especially at lower levels of screen brightness? What about other controllers? What is your opinion on using those dark colors?

11) Do controllers typically adjust screen brightness? When do they do so and how often? (maybe during night shift?)

Preferences:

1) How many colors you would prefer to have on a single display before you feel it interferes with overall performance?

2) Are controllers allowed to customize the color–settings on the display? If so, does this present any problems for supervisors? Does this cause any problems during the transition when another controller assumes control of the position?

3) Would you prefer to have such color customization or rather not?

4) In some displays, a single color is used to represent several different types of information (i.e., multiple sets of color-coding). How do controllers feel about that? Does multiple color-coding bother them?

5) Bright colors such as red are often used to draw one's attention. Do you feel that the use of bright colors on existing displays is so compelling that you might overlook other critical information?

6) Colors are used to separate information. As presently used, does this appear to assist controllers in integrating information? Are there instances where it seems to interfere with information processing?

7) Can the colors be named easily and consistently across controllers? Have you ever experienced that two controllers name a colored sign differently?

8) Can the colors on your display be easily distinguished from each other? Are there any colors that cause confusions in naming them? Are there any colors that you would recommend not using on an ATC display?

Observation:

1) How many monitors and keyboards are there at a controller's workstation?

2) Are the keyboards color-coded?

3) What are the typical view angles of controllers relative to the monitors/displays? Are there side-view and / or head-up views?

4) What is the typical viewing distance from a controller to the monitors/displays?

5) Are the monitors LCD or CRT?

6) Is the facility still using paper strips?