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Exploring the Relationship between Operational Errors and Color Vision Deficiency

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12. Abstract

We analyzed Operational Error (OE) data and data from the Office of Aerospace Medicine that identified 87 Color Vision Deficient (CVD) Air Traffic Control Specialists (ATCSs) to explore the relationship of color vision deficiency with the occurrence of OEs. Our first analysis searched 70 OE narratives, recorded across 12 years, for OEs where CVD ATCSs were involved. We found no reports that identified color vision or the inability to distinguish colors as a possible contributor to a loss of separation. Next, we attempted to determine if CVD ATCSs were involved in a similar number of OEs as their Color Vision Normal (CN) co-workers. We compared number of OEs occurring from 1995 to 2006 for 87 ATCSs identified as CVD with two sets of matched pairs of CN ATCSs to determine if CVD ATCSs were at a greater risk of being involved in an OE as compared to CN ATCS. We matched CVD ATCSs with CN ATCSs who had the same number of years of experience, worked in the same type of facilities, and were approximately the same age. The comparison of the number of OEs between the three groups was inconclusive due to the small effect size associated with the occurrence of OEs and the resulting lack of statistical power. However, a significant difference was found between the number of OEs in which CVD ATCSs were implicated during the time period from 2001 to 2006 as compared with the time period from 1995 to 2000. The number of OEs in which CVD ATCSs were involved went up after the introduction of ATC display systems in the year 2000 that made more use of color.

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List of Abbreviations

Acronym	Abbreviation Explained
ATCS	Air Traffic Control Specialist
CAMI	Civil Aerospace Medical Institute
CARTS	Color Automated Terminal System
CN	Color Vision Normal
CVD	Color Vision Deficient
DSP	Departure-Spacing-Program
DSR	Display System Replacement
FAA	Federal Aviation Administration
IDS	Information Display System
NAS	National Air Space
OE	Operational Error
PIP	Pseudo Isochromatic Plate
STARS	Standard Terminal Automation Replacement System
TRACON	Terminal Radar Approach Control

Executive Summary

With the increased use of color-coding in Air Traffic Control (ATC) displays, the ability to identify and discriminate colors becomes increasingly important in the safe performance of ATC tasks. In 2007, we conducted a study to determine the extent to which color vision deficiencies were implicated in Operational Errors (OEs) (Crutchfield and Lowe, 2010). We conducted the study to determine if Color Vision Deficient (CVD) Air Traffic Control Specialists (ATCSs) can perform critical tasks safely and not pose a significant safety hazard in terms of OEs as compared to ATCSs with normal color vision. Although the term OE and the associated OE investigation process are no longer used within the FAA, we document the results of that study now, in this report, to inform future discussions regarding the use of color on ATC displays.

We conducted three analyses. In our first analysis, we searched 70 OE narratives recorded for OEs where CVD ATCSs were involved. This analysis yielded no instances where color vision or the inability to distinguish colors was documented as a possible contributor to a loss of separation.

Next, we attempted to determine if CVD ATCSs were involved in more or fewer OEs than their CN co-workers. We analyzed OE data from 1995 to 2006 for 87 CVD ATCSs and two sets of matched pairs of Color Vision Normal (CN) ATCSs. We matched CVD ATCSs with CN ATCSs who had the same amount of experience, worked in the same type of facilities, and were approximately the same age. Our comparison of the number of OEs between the three groups was inconclusive due to the small effect size associated with the occurrence of OEs and the resulting lack of statistical power.

In our final analysis, we compared the number of OEs occurring before and after the implementation of new primary situation displays for TRACON and en route. As new displays were implemented after 2000, we compared the number of OEs that occurred between 1995 and 2000 with the number that occurred between 2001 and 2006 for both the CVD and CN

groups. For CVD ATCSs, we found a significant difference in the number of OEs between the two time spans. The number of OEs in which CVD ATCSs are involved went up after the introduction of new ATC displays.

1. Introduction

In 1978, the Federal Aviation Administration (FAA) started screening Air Traffic Control position applicants for color vision deficiencies using clinical color vision tests. The color vision screening process was based solely upon the results of Pseudo Isochromatic Plate (PIP) tests (Milburn, N., 2004; Xing, J., and Schroeder, D.J., 2006a). Due to requirements from the Uniform Guidelines on Employee Selection Procedures stating that selection procedures must predict job-related outcomes, however, by 1985 the FAA had altered the screening process to allow controller applicants who failed the PIP test to take job-related color vision tests as well (Pickrel and Convey, 1983; Mertens, 1990). The FAA hired applicants who passed the job-related test under a waiver and thus did not keep applicants out of the Air Traffic Control Specialist (ATCS) occupation solely because of failure on a clinical color vision test.

From the mid-1960s to the mid-1990s, the Air Traffic Control (ATC) tasks that required color recognition involved (a) identification of red and black text on flight progress strips for radar ATCSs and (b) identification of red, green, and white signal lights used at airports for tower ATCSs. Thus, in 1992, the FAA began using two separate operational, practical, job-related color vision tests developed by Mertens et al. (1990, 1992) that were based specifically on these controller tasks. The FAA revised medical guidelines to allow an applicant who failed the PIP test to be reevaluated using the practical tests relevant to his or her work option (Milburn, N., 2004). Mertens and his colleagues found that about 10% of applicants who failed the PIP tests could pass their practical test and, therefore, could be considered qualified. However, with the advent of new ATC systems that have utilized color coding far beyond the prior operational environment, the potential existed for errors related to color vision deficiency to become an unrecognized hazard.

We conducted a study in 2007 to help shed light on whether Color Vison Deficient (CVD) ATCSs can operate safely and not pose a potentially greater air traffic safety hazard, in terms of a greater risk for operational errors, than Color Vision Normal (CN) ATCSs when using displays with color-coding (Crutchfield and Lowe, 2010). The focus of this study was to determine the extent to which CVD ATCSs are involved in ATC operational errors. Based partially on the results of this study, the FAA went on to develop other practical color vision tests to use in the selection process (Chidester, Milburn, Peterson, Gildea, Perry, Roberts, 2013). We publish the results of the 2007 study here now with the intent to make them available to guide future decisions regarding the safe performance of ATCSs who have color vision deficiencies and the development of complex displays that rely on the frequent use of color-coded cues.

An operational error (OE) was said to result when a controller failed to maintain required separation between aircraft, terrain, and other obstacles that would interfere with safe flight (FAA, 2006R). OEs were rare, considering the high volume of operations handled by our National Airspace System (NAS; Broach and Schroeder, 2005). When an OE occurred, a preliminary investigation was conducted to determine whether the OE was the result of a controller action (or inaction), an equipment malfunction, or some other factor that was not under the direct control of the ATCS. If the preliminary investigation revealed that the OE probably occurred because of an ATCS human error, then a formal investigation was conducted to determine what ATCS actions or inactions caused the OE. Even though the primary purpose of the investigation was to record the facts of the incident, rather than provide a detailed human factors analysis of the situation, it was from the investigations that databases were created to analyze OE trends. Because of medical privacy issues, medical conditions such as color vision deficiencies were not captured on the investigative form.

Color vision deficiency may have been a potential contributor to OEs because much of the information that ATCSs use in their tasks is redundantly color-coded information on ATC workstation displays. The displays in use during the time of our analyses were classified by Xing and Schroeder according to their functionality (2006a). The primary displays are used to monitor dynamic traffic and make the necessary changes to maintain separation; therefore, it is the display of most interest with respect to an OE. Secondary displays are decision-support displays from which ATCSs acquire additional information about the air traffic situation. Information displays provide static or slowly updated advisory information used mostly for planning purposes when the ATCS is not fully occupied with controlling traffic. Secondary displays are usually not in the ATCSs' immediate operational work area.

For en route ATCSs at the time of this study, the primary display was a radar display referred to as the Display System Replacement (DSR), and it used color only for its graphics tool and weather information (Xing and Schroeder, 2006a). The DSR was implemented at en route facilities throughout the year 2000. The secondary displays for en route ATCSs, which include the soft-CRD (Computer Read-out Device) and URET (User Request Evaluation Tool), use a greater variety of colors than the DSR. The DSR has since been replaced by the En Route Automation Modernization (ERAM) system.

At the time of this study, the primary displays for TRACON ATCSs were the Color Automated Terminal System display (CARTS) and the Standard Terminal Automation Replacement System (STARS). The Arts Color Displays (ACDs) began implementation at facilities in the year 2000. Secondary displays include the Information Display System (IDS) and the communication system. Similar to en route facilities, TRACON advisory displays also used the most color in the facility. These include the Parallel Runway Monitor tool and the Departure-Spacing-Program (DSP). Many of the TRACON systems are currently being replaced by the Terminal Automation Modernization and Replacement (TAMR) system.

Many of the displays in towers are a modified version of TRACON displays. However, since most of the tower ATCSs' tasks involve out-the-window observations, there is no primary display for ATCSs working in traditional towers (although the video walls recently implemented for remote towers may be considered primary displays). Tower ATCSs look out the window to monitor aircraft movement and identify aircraft by their exterior logos, colors, and the colored lights on the aircraft. They utilize the Tower Workstation Display, which is a modified version of STARS, as a secondary display (Xing and Schroeder, 2006a). Advisory displays vary across towers but mostly consist of weather information displays.

DSR and STARS are two examples that illustrate a general increase in the use of color in ATC displays (Xing and Schroeder, 2006a) over their predecessor displays. With the increase in color usage, the ability to identify and discriminate between colors could theoretically become increasingly important in the performance of ATC tasks. The increased use of color could put CVD ATCSs at a greater risk of misinterpreting displayed information, which could lead to an OE. According to an informal analysis by Xing and Schroeder (2006a), as many as one-third of the OEs at one facility might be associated with color-coding on an ATC display.

In this study, we analyzed archival data regarding OEs and ATCS color vision abilities in an attempt to explore the relationship between OEs and color vision deficiency. Our first analysis looked at the OE narratives recorded for OEs where CVD ATCSs were involved. Our second analysis attempted to determine if CVD ATCSs were involved in more OEs than their CN counterparts. We matched CVD ATCSs with other CN ATCSs who had the same amount of experience, worked in the same type of facility, and were approximately the same age. We then compared the number of OEs in which these ATCSs were involved with the numbers for the matched pairs. Our final analysis compared the number of OEs that occurred before and after the implementation of newer displays for CVD and CN ATCSs.

2. Methods

2.1. Participants

This study used archival data and did not involve the active participation of any participants. The archival data were from FAA Air Traffic Control Specialists (ATCSs; occupational series 2152). The sample included 87 ATCSs with a record of color vision deficiencies and 174 ATCSs for which we had no record of color vision deficits, used as matched pairs.

2.2. Materials

Three sets of archival data were used in the performance of this study. The first set of data was provided by the Office of Aerospace Medicine and consisted of a list of the names of currently employed (August 2006) CVD ATCSs. The list was derived from the Covered Position Decision Support System (CPDSS). The CPDSS contains information regarding the initial and periodic follow-up medical examinations of ATCSs. A representative from the Aerospace Medical Certification Division at the Civil Aerospace Medical Institute (CAMI) in Oklahoma City conducted a query of the CPDSS using available examination records and generated a preliminary list of CVD ATCSs within each region. We asked that each of the regional flight surgeons check the data for their region and determine if additional names should be added to the list. This process identified an additional 7 for a total of 94 CVD ATCSs employed by the FAA as of 2006. The list did not include biographical information or the exact type of color vision deficiency for any ATCSs on the list.

The second set of data was provided by the Federal Aviation Administration Payroll and Personnel System and consisted of a database listing biographical and employment information for all FAA employees between the years 1995 and 2006. The final set of data was a database that contained a record of OEs that occurred at FAA ARTCCs, TRACONs, and Towers during the 1995 to 2006 time period. This database identified ATCSs who were involved with OEs.

2.3. Design and Procedure

For the purpose of protecting confidentiality, the databases used in this study were reduced and redacted, and copies of the databases provided (as described above) were deleted once the necessary information was extracted. The databases were reduced in three phases.

The first phase reduced the database of employment data. All information excluding name, social security number, job title, age, date of birth, sex, tenure, facility type, and facility identifier was deleted from this database. Following this, all employees who were not ATCSs were also deleted from the database.

In the second phase, matched pairs were found. We matched each CVD ATCS with two ATCSs who were CN. We equated across the three groups on the following variables: sex, tenure, type of control facility, grade of control facility, and age. The matching was performed to reduce the variance in operational errors that can be due to other factors apart from color vision deficiencies, as well as to equate group sizes for the purposes of statistical analysis.

The matching was conducted by first locating the names and social security numbers for each CVD ATCS participant in the employment database. Once we located them in the database, we were able to find the age, sex, tenure, and facility type for each CVD participant. We then found two sets of matched-pair participants that matched the criteria for age, sex, tenure, and facility type. Once the CVD participants and all possible matched pairs were identified, data for all other ATCSs were deleted from the database. Grade levels that provide a relative approximation of the amount of air traffic operations a facility contends with on a yearly basis were matched to each of the facility identifiers. The facility identifiers were then deleted. At this time, the database of all possible matched pairs was further reduced to only include those that matched the facility grade levels of the CVD participants. From this reduced list, the two closest CN matches were selected for each CVD participant, and data for all other ATCSs were deleted.

After linking the CVD names with biographical and employment information, we were able to determine that it was not appropriate to use data from all CVD individuals on our list. Individuals who were employed in tasks where the opportunities to control traffic were potentially not as great as for the other 2152s (such as Air Traffic Control Supervisors) were not included for subsequent analysis. Furthermore, after performing the matching procedure, we learned that we could not always match individuals by the age category. Any CVD individuals we could not match within 5 years of age with at least two other CN ATCSs were also excluded from subsequent analysis. The reduced data set included 87 CVD ATCSs and 174 CN ATCSs.

In the third phase, OE data for the selected participants were found. Participant numbers were assigned to indicate the relationship between a CVD participant and its matched pairs. At this point, it was no longer necessary to retain age and sex for the participants selected. Therefore, this information was removed from the database as well. The names, date of birth, and social security numbers from the reduced employment database were located in the Operational Error database. For each participant and each year between 1995 and 2006, all occurrences of OEs were identified and tallied. At this point, the narratives associated with the OE reports for CVD ATCSs were copied and set aside for later analysis. The frequency of OEs by year was merged with the reduced employment database. Once this was completed, it was no longer necessary to retain name, date of birth, and social security number, so these three pieces of information were also deleted. The remaining databases were used in both the analysis of narratives and the analysis comparing OE frequencies. The database used in narrative analysis contained only the narratives of OE reports where CVD ATCSs were involved. The database used for OE frequency analysis included membership in CVD or CN groups, matched-pair linkage, tenure, job title, facility type, facility grade level, and frequency of operational errors per year (1995-2006) only.

3. Results

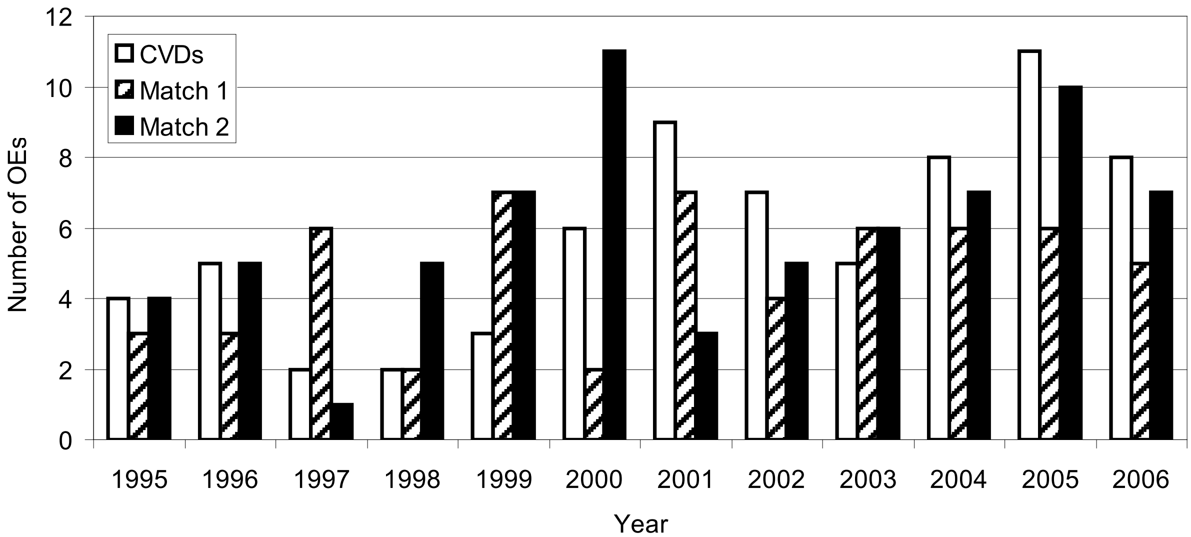
3.1. Operational Error Narrative Analysis

We found a total of 70 reports of OEs, logged for the years from 1995 to 2006, associated with CVD ATCSs. We read the report narratives of these 70 OEs to determine if any of them included any indication that an inability to distinguish color played a role in the loss of separation. The primary purpose of OE narratives is to recount the events around a loss in separation. The OE narrative is not intended to speculate about what may have caused an OE. However, if any evidence of problems with color discrimination might have been associated with an OE, it would be noted in the narrative section. In reviewing these 70 cases, we found no mention of color vision deficiency or the inability to distinguish color as playing a role in the occurrence of any loss of separation.

3.2. Operational Error Frequency Analysis

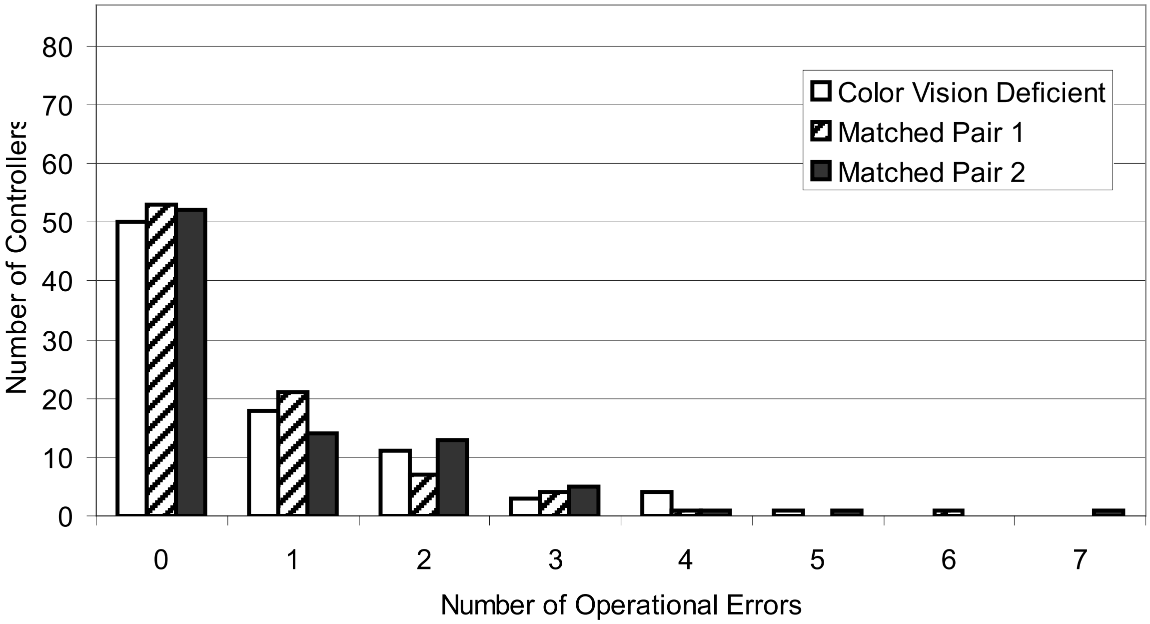
The number of OEs that occurred between 1995 and 2006 was tallied for each of the three groups (CVD, CN Match 1, CN Match 2). The number of OEs per year for each of the three controller groups is shown in Figure 1. The overall number of OEs seemed to increase from 1995 to 2006. This trend is consistent with other studies that have suggested OE occurrences are related to overall changes in the amount of traffic (FAA, 1988), and traffic generally increased across the years during this time. It also appears that the CN groups had more errors than the CVD group in some years and fewer in others. The tally of OEs for the CVD group often appears higher than that of the CN groups from 2001 to 2006. However, in cases where the CVD group had a higher tally, the tally was no more than two OEs higher than the nearest number of OEs for a CN group. Across all 12 years, the 87 CVD ATCSs were involved or associated in a total of 70 OEs. The first matched-pair group was involved or associated in a total of 57, and the second matched-pair group, a total of 71. Compared to an average of the matched-pair groups, 64, CVD ATCSs seem to have slightly more OEs than the matched CN ATCSs. However, inferential statistics will need to be applied before we can tell if the difference in the number of OEs is significant.

Figure 1
Number of operational errors per year for each of the three controller groups.



The frequency of OEs for the three controller groups analyzed in this study is depicted in Figure 2. From Figure 2, we can see that the distribution of OEs does not resemble that of a normal curve but instead is positively skewed. The majority of ATCSs in our sample were not involved/associated in any OEs between 1995 and 2006. Although these data support the presumption that the air traffic control system maintained a high level of safety, it has two major implications for our analysis. One implication is that the statistical tests to be used in analyzing these data should not be based on assumptions that the distribution of means across samples is a normal distribution. The second implication has to do with statistical power. It is known that research on rare events, such as OEs, can pose serious challenges to analysis (Broach and Schroeder, 2005; Schroeder et al., 2006). Data of this nature are often associated with small effect sizes, and thus, inferential analyses may require large sample sizes to attain the power necessary to find significant differences, even where differences may actually exist. For our analyses, the small number of CVD ATCSs makes it impossible to attain a large sample size.

Figure 2
Distribution of OEs.



We next analyzed the number of OEs for each group to see if statistically significant differences could be found. If inferential tests show a significant difference between the groups, then we can state, with a relatively small probability of error, that the number of OEs found for each group is not the same. Alternatively, if the results of the statistical tests do not show a significant difference, what we can state about our findings depends on the statistical power of the test. If our tests have sufficient statistical power and the results show no significant differences are found, then we can state that our analysis supports the conclusion that neither group of ATCSs has more OEs than the other. Unfortunately, if there is not sufficient statistical power, then a test result of no significant differences is, at best, ambiguous. If our tests have insufficient statistical power, then they are as likely as not to find a significant difference, even where a significant difference truly does exist.

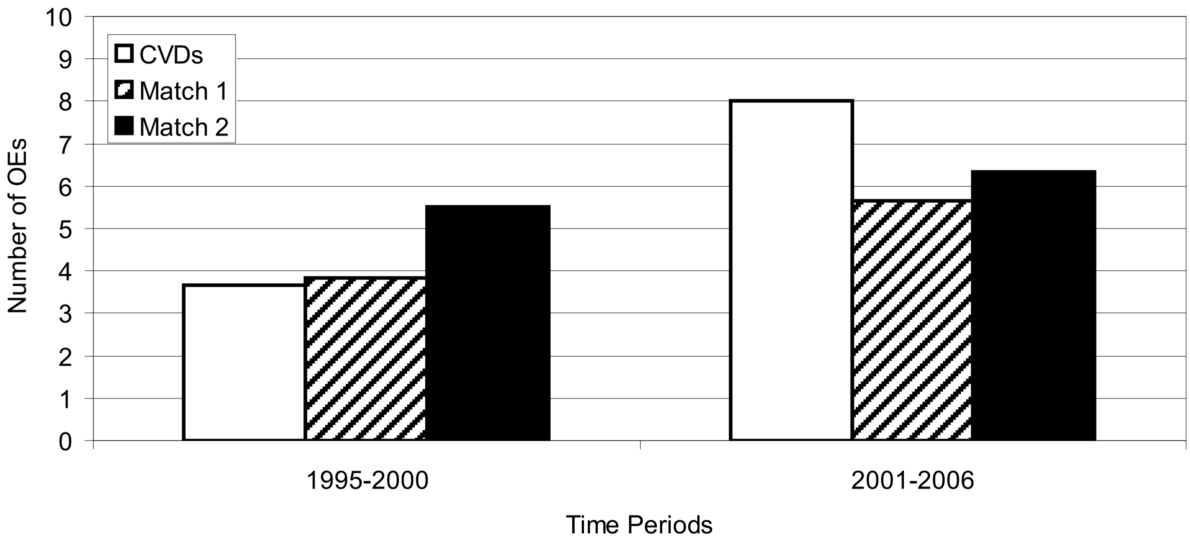
A Friedman χ^2 test was conducted to determine statistical differences between the number of OEs found for each of the controller groups. The Friedman test is appropriate because OE counts are frequency data and thus not continuous data, the CVD ATCSs were matched with ATCSs that had similar characteristics and thus were not independent, two matched pairs were used in the analysis, and the distribution of OEs was clearly non-normal. Although parametric tests of inference are usually more powerful than nonparametric tests, the power of parametric tests can be less in cases where the assumptions of normality have been seriously violated (Toothaker and Miller, 1996, p. 579). The Friedman test did not find a significant difference between the number of OEs associated with the three groups (two CN groups and one CVD group).

Given the rare nature of OE occurrences, a post hoc power analysis was performed to determine the reliability of the Friedman test result. A Cramér's Φ was calculated and compared to a table of equivalents for effect sizes provided by Cohen (1988, p 222). The effect size value was used along with the values for number of participants and degrees of freedom to calculate power using the G*Power 3 program (Faul, Erdfelder, Lang, and Buchner, 2007). The power of the Friedman's test in our study was .37. The results of our power analysis suggest that there is only a 37% chance that our test would find a significant difference if one actually does exist. Due to the fact that the effect size associated with the occurrence of OEs is small, we would need roughly four times the number of CVD ATCSs before we would have enough statistical power to determine, with a 95% chance of certainty, whether CVD ATCSs were implicated in the same number of OEs as CN ATCSs.

We know that new primary displays featuring a greater use of color information were implemented in both the en route and TRACON environments during 2000 and 2001. A look at Figure 1 would seem to suggest that a possible change in the relationship between the number of OEs and color vision occurs after the year 2000. For this reason, further analyses were conducted comparing the number of OEs for CVD and CN matched pairs for the years 1995 to 2000 and 2001 to 2006 separately. Again, no significant differences were found. However, subsequent power analyses indicated that these tests had even less power than the previous test across all 12 years and, thus, once again, a failure to find a significant difference in this situation cannot be considered conclusive.

Finally, comparison tests were conducted to determine if the number of OEs in which each of the groups was implicated for the years 2001 to 2006 was greater than the number in which each was implicated for the years 1995 to 2000. The average number of OEs for each group during the two time periods is shown in Figure 3. As these comparisons were conducted separately for each of the three groups, a Wilcoxon test was applied. No significant differences were found between the two groups of years for either of the CN groups. However, a significant difference was found for the CVD group $\chi^2(2, N = 87) = -2.767$, $p = .006$. The number of OEs was significantly greater in the years 2001 to 2006 than in the years 1995 to 2000 for the CVD group.

Figure 3
Average number of OEs for each group over a six-year time period.



4. Conclusion

This study attempted to increase our understanding of potential air traffic safety risks associated with color vision deficiency by exploring the relationship between OEs and ATCS color vision ability. We reviewed narratives associated with OEs attributed to CVD ATCSs and compared the number of OEs associated with CVD ATCSs with the number of OEs associated with CN ATCSs who were similar in age and experience and worked at similar ATC facilities. Unfortunately, the results of these analyses were inconclusive. It is possible that if color played a role in the occurrence of an OE, it might not be recorded in an OE report at all. Furthermore, due to the rare nature of OEs, our statistical tests did not have sufficient power to determine whether the number of OEs attributed to CVD ATCSs was the same as that attributed to CN ATCSs.

One interesting relationship found during our analyses, however, has to do with the number of OEs attributed to CVD ATCSs over time. The number of OEs attributed to CVD ATCSs was significantly greater during the time period from 2001 to 2006 than it was for the time period from 1995 to 2000, whereas no difference was found across those same two time periods for the CN controller groups. As this study relied upon archival data, it is difficult to say what exactly led to this increase in OEs. These findings, however, are consistent with two theories related to color vision ability. One is that as people age, their color vision ability declines. If the risk of OEs becomes greater as color vision deficiency becomes worse, then the increase in OEs could be due to the color vision of these ATCSs declining past a threshold that ultimately affects their job performance, as opposed to the CN ATCSs, whose color discrimination may have declined but not yet reached the threshold that affects performance. However, it should be noted that the ATCSs in this case are only aging an average of 6 years between the two time periods. The second theory is that something about the new displays implemented in the 2001 time frame interacted with color vision deficiency to make it more difficult for CVD ATCSs to do their job. The aspect of the new displays that could be problematic might be an increased use of color, the use of colors that are more difficult to distinguish, or a change in display brightness or display format that otherwise makes it more difficult for a CVD controller to compensate for a lack of color vision. The cause may be due to a combination of the two theories above or something that has not yet been identified. However, we will likely not know the answer without a more in-depth analysis that controls more of the extraneous variables involved.

With an increase in the use of color by new ATC displays, it has become increasingly important to know if CVD ATCSs pose a greater risk to air traffic safety. In response to this increase, it would be helpful for reporting systems that have since replaced the OE procedure to begin providing information on whether a display's use of color was a factor in a particular situation. Although OE reports did not currently prove to be a very useful tool to answer our questions about the ability to distinguish color and its impact on air traffic safety, other methods and measures might. Nonetheless, until we can show that color vision deficiency played no role in the increased OE rate, we are compelled in the interest of safety to implement the necessary safeguards. In the future, for example, studies could be conducted in a laboratory setting where the presentation of color information can be controlled and its impact assessed through other performance and safety-related measures, such as response latencies, keystroke errors, and measures of dynamic comprehension.

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