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Effects of Color Vision Deficiency on Detection of Color-Highlighted Targets in a Simulated Air Traffic Control Display

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16. Abstract

The present study sought to evaluate the effects of color vision deficiency on the gain in conspicuity that is realized when color-highlighting is added as a redundant cue to indicate the presence of unexpected, nontracked aircraft intruding in controlled airspace. Sixteen subjects with severe color vision deficiency of both protan and deutan types and eight subjects with normal color vision performed a simulated high-workload air traffic control task over a 1-hour period. Displayed information was normally green. In addition to the primary task, subjects also monitored for occasional intrusions by light aircraft identifiable on the basis of triangular shape alone or with the color red added as a redundant cue. The luminance of the red color was also 30% higher. Detection of red targets was slightly slower than detection of green targets in protans. In contrast, detection was faster with red targets for both normals and deutan subjects. Impairment in performance of the severe protans with red highlighting was attributed to their well known reduced sensitivity to red light. Although severe deutans have reduced color discrimination, they do not usually have reduced sensitivity, and their performance was probably enhanced by the greater brightness of red targets. These results demonstrate that the approach of using color always as a redundant cue to ensure performance of color deficients, is valuable, but the potential for adverse interaction of color coding with color deficiency must always be considered.

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EFFECTS OF COLOR VISION DEFICIENCY ON DETECTION OF COLOR-HIGHLIGHTED TARGETS IN A SIMULATED AIR TRAFFIC CONTROL DISPLAY

INTRODUCTION

Advanced aviation systems are increasingly using color coded electronic information displays. Their inherent flexibility and utility is in large part due to benefits derived from color coding. Color can be used for decluttering and organizing information in displays, as well as for coding and enhancement of display esthetics (Christ, 1975; Silverstein and Merrifield, 1986; Society of Automotive Engineers (SAE), 1988). The attention-getting value of color highlighting is another important benefit demonstrated in studies of visual search (Carter and Carter, 1981; Carter, 1982). It has also been suggested, however, that the attention-getting value of color in electronic displays may be reduced in individuals with defective color vision; while others have argued that by using color always as a redundant cue, the performance of color deficients can be protected (Silverstein and Merrifield, 1986; Cole and Macdonald, 1988). This study sought to explore further the potential for adverse effects of color vision deficiency on potential conspicuity gains from color-highlighting in detection of nontracked VFR aircraft unexpectedly intruding in controlled airspace. The symbols concerned with other monitoring tasks performed simultaneously, and "clutter" normally present in the simulated ATC traffic display, were green. The detectability of red highlighted symbols was compared to green symbols in the task of detecting intruders.

Predictions

- Detection times among both normals and color deficients would be similar for green, non-highlighted intruder symbols.

- Detection times among normals would be significantly lower for detection of red highlighted intruder symbols than for green.

- Effectiveness of red highlighting would be somewhat impaired in deutans, relative to normals, because of reduced apparent color difference between red and green.

- Effectiveness of red highlighting would be considerably diminished in protans, relative to normals, because of their well-known reduced sensitivity to red light (Wyszecki and Stiles, 1982) in combination with reduced color discrimination ability.

METHOD

Subjects

Eight subjects with normal color vision, 8 having severe color vision deficiencies of the protan type, and 8 having severe deficiencies of the deutan type were selected. In both the protan and deutan groups, half of the 8 subjects in each group were diagnosed as extreme anomalous trichromats and half were dichromats. All were college students 18 to 29 years of age, with at least 20/30 acuity, and they were paid an hourly wage. The color vision diagnosis was performed with the Nagel Type I anomaloscope (Schmidt-Haensch) using the Linksz procedure (Pokorney, et al, 1979). Half each of both protans and deutans were extreme anomalous trichromats and the remainder were dichromats.

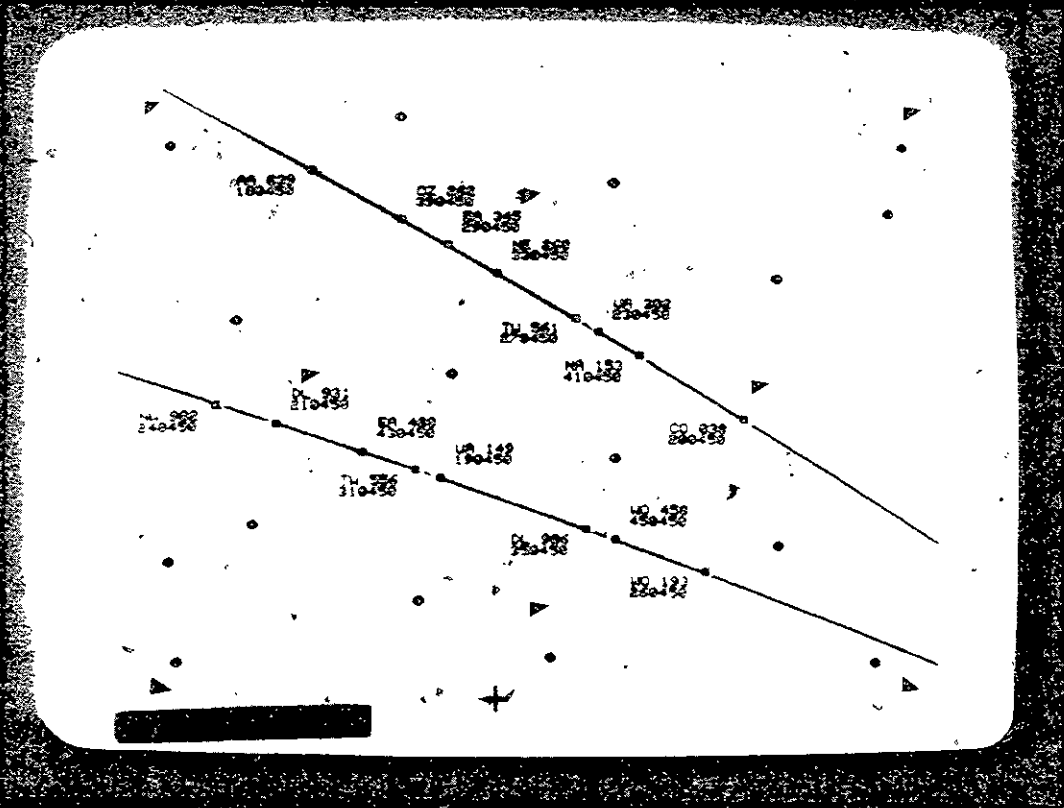
Apparatus and Task Description

The ATC display was generated by a Digital Equipment Corporation (DEC) VS11 19-inch (49-cm) graphics monitor controlled with a VAX 11/730 computer. The primary task consisted of monitoring for 2 types of critical events. The first type was readily detectable and consisted of the appearance of 3 X's in place of the three altitude numbers in a given data block. Subjects were told that the 3 X's signified that a malfunction had occurred in an aircraft's altitude transponder. The second type of critical event was considerably more difficult to detect because it was not immediately apparent: 2 aircraft at the same altitude on the same flight path. If the event was not detected within a predetermined time limit, a "conflict alert" occurred signifying a possible conflict situation. Any time a possible conflict was detected, either by the subject or following a "conflict alert" alarm, the subject had to decide whether a conflict existed or not (whether the 2 aircraft were flying directly toward each other, or not). For both types of critical events in the primary task, subjects performed appropriate responses to resolve the problems. Subjects were always controlling 16 aircraft; when one left the screen, another entered the screen in a few seconds. The primary tasks have been described more completely elsewhere (Thackray and Touchstone, 1989).

The "secondary" task, the detection of triangular targets representing nontracked aircraft, was the test of primary experimental interest. The triangles were similar in size to dots that were added to the display to produce clutter. Triangles could appear at any 1 of 8 different locations; 4 of the locations were near the extreme corners of the display and 4 were more centrally located. Figure 1 shows all of the possible triangle locations as well as the clutter and a typical pattern of alphanumeric targets representing controlled aircraft and their data blocks. The triangles representing intruder aircraft were presented as either red or green. Whenever a VFR target was detected, a console button was pressed and the target would disappear shortly thereafter. A target would also disappear if not detected within a 90-second timeout period.

Figure 1

Subject's display showing clutter, all triangle locations, and a typical pattern of alphanumeric targets.



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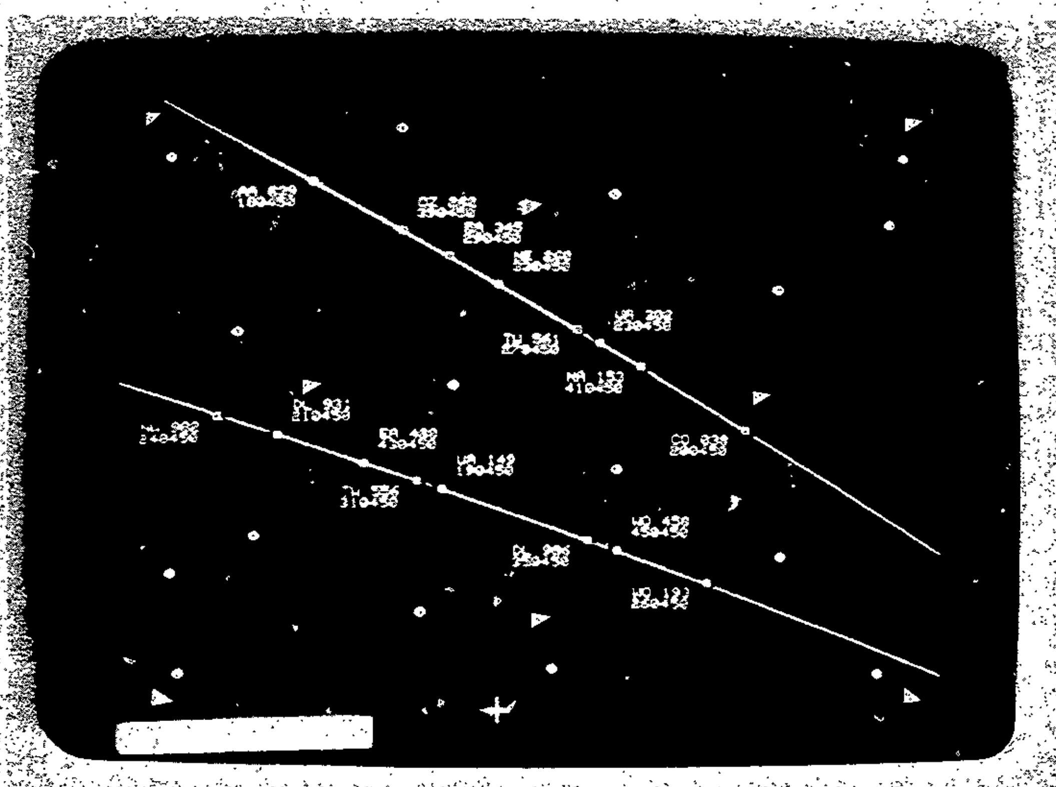

Eighteen primary task and 4 secondary task critical events occurred during a 60 minute experimental test session, with no more than 1 event present at any given time. Time of occurrence of each type of event was fixed. Location of each successive secondary task target, however, was randomly assigned without replacement for each subject. Thus, although interstimulus intervals were fixed for triangular targets, the order of locations differed for each subject. Subjects were given no information regarding the frequency of events or their order of occurrence. Two video cameras were used to monitor both the subject's facial orientation and the visual display to enable analysis of the subject's visual behavior during times when secondary targets were presented. Ambient illumination (23 lux at the display) was comparable to the lighting of the radar displays measured at an en route center.

Color and Luminance Measurement and Specification

All color and luminance measurements were made using a Photo Research spectroradiometer. The particular red and green colors used were selected from the available DEC VS11 colors and were chosen to be as close as possible to the CIE coordinates (red X=.650, Y=.336; green X=.329, Y=.600) specified for the FAA's Advanced Automation Sector Suites that are currently under development. While it was not possible to achieve a perfect match of the red/green luminances with the VS-11 display, luminances of the colors selected were reasonably close. Color and luminance values are shown in Table 1. The luminance of the red color was unavoidably 30% higher than the green.

Table 1

Color and Luminance Values of Display Elements

Display Elements	Hue	CIE Coordinates X	CIE Coordinates Y	Luminance (in foot-lamberts)
Alphanumerics	Green	.233	.628	4.94
Clutter	Green	.233	.628	4.94
Triangle	Green	.233	.628	4.94
Triangle	Red	.615	.342	6.72

Procedure

Subjects received detailed training for each type of task event along with the appropriate responses to each. Short practice sessions followed the description of each type of event, and a final combined session provided practice on all primary and secondary task events and also familiarized subjects with the conflict alert alarm.

Following the practice sessions, subjects completed a 9-point subjective rating scale to describe their present feelings of attentiveness, tiredness, strain, boredom, and irritation. The final set of task instructions explained that the conflict alert alarm was essentially the same as that used in contemporary ATC systems to warn controllers of possible conflict situations, and that in this particular experiment, the alarm would go off whenever the computer determined that they had failed to detect a possible conflict in the minimal allowable time. Subjects received a bonus contingent upon the number of conflict alerts that occurred during the experimental session. Background noises recorded in actual air traffic control radar rooms played continuously during the experimental testing session. At the completion of the session, subjects were administered a second version of the rating scale that contained additional items relating to perceived task difficulty and the amount of effort required to maintain task concentration; debriefing concerning the purposes of the experiment followed.

RESULTS

Detection Times for VFR Intruder Targets

Missed appearances of VFR intruders were rare. Only 2 intruder targets were missed during the 1-hour experimental session, both by protans. One missed intruder target was of green color; the other was red. Those 2 events involving missed targets were arbitrarily assigned a value of 90-seconds (the time limit for detection), and were averaged in with detection latencies in order to yield a single overall measure of detection performance. Mean detection latency for the 1-hour experimental session is shown in Figure 2 as a function of color of VFR intruder targets (green and red triangles) and color vision deficiency. The corresponding standard deviations and 95% confidence limits of detection times for the 3 vision groups are shown in Table 2. The specific experimental hypotheses concerning lack of difference between color vision groups in detection of green intruder targets, and the beneficial effects of red highlighting in normals and individuals with color vision deficiency were evaluated by planned comparisons using t-tests and are shown in Tables 3 and 4. There were no significant differences among the 3 color vision groups in detection of green triangles. Detection times were significantly shorter for red triangles than for green in both normals and deutans. Detection times were longer for red triangles in protans, but not significantly so.

As mentioned above, only protans missed triangles; normals and deutans missed none.

Primary Task Performance

Mean frequency of occurrence of conflict alerts is shown in Figure 3 as a function of color vision. Statistical analyses of these data revealed no significant differences as a function of color vision classification.

Mean times to detect altitude malfunction events for subjects in the 3 Color Vision Groups are also shown in Figure 3. Again there were no significant effects of color vision classification.

Subjective Data

Although all 3 groups exhibited a decline in attentiveness, accompanied by increases in tiredness, strain, boredom, irritation, and effort from beginning to end of the session, there were no significant differences between color vision groups in the subjective data.

DISCUSSION

The most important finding of this study concerned the failure of protans to benefit from the alerting effect of red highlighting of symbols representing intruder aircraft. That effect is in

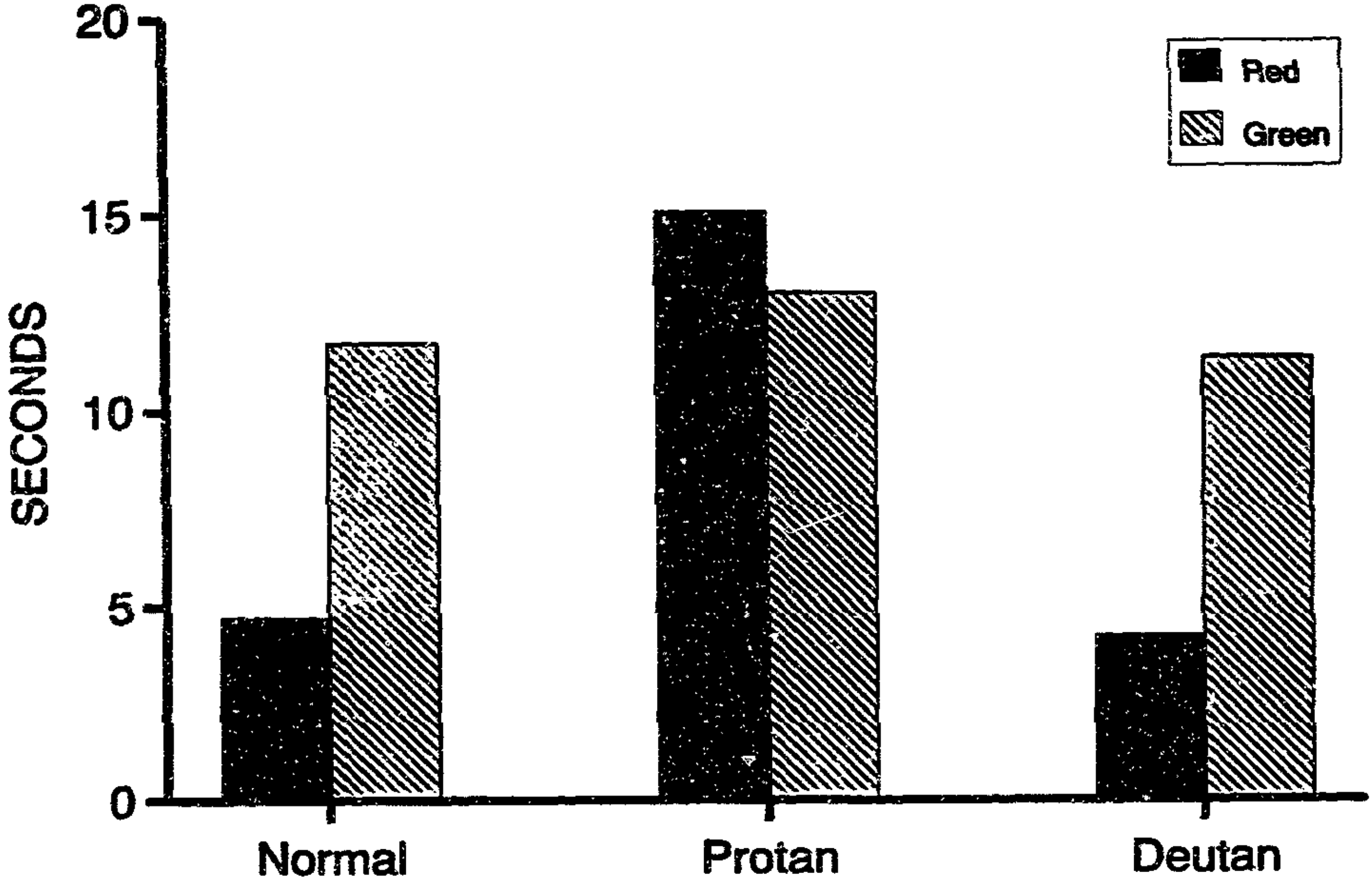

Figure 2

Mean Detection Time for Red and Green Intruder
Aircraft Targets for Each Color Vision Group

Table 2

Mean Detection Time for Green and Red Triangles as a Function of Color Vision

Green Triangles

Group	Mean	S.D.	95% Confidence Interval
Normal	11.77	10.78	2.76 to 20.78
Protan	13.05	15.28	0.27 to 25.82
Deutan	11.37	7.98	4.75 to 18.11

Red Triangles

Group	Mean	S.D.	95% Confidence Interval
Normal	4.72	6.91	-1.05 to 10.50
Protan	15.11	17.26	.67 to 29.54
Deutan	4.23	3.81	1.04 to 7.43

Table 3

Difference Between Detection Times for Green and Red Triangles in Each Color Vision Group

Group	Green-Red Difference (SEC)	T	DF	P
Normal	7.05	2.41	7	.02*
Protan	-2.06	-0.24	7	.40
Deutan	7.14	2.16	7	.03*

*Significant at the .10 level, 1-tailed test

Table 4

Difference in Detection Times Between Color Vision Groups

Green Triangles	Difference (SEC)	T	DF	P
Normal - Protan	-1.28	.19	12.6	.42
Normal - Deutan	.40	.07	12.9	.47
Deutan - Protan	-1.68	.26	10.6	.39
Red Triangles				
Normal - Protan	-10.39	1.58	9.2	.07*
Normal - Deutan	.49	.17	10.9	.43
Deutan - Protan	-10.88	1.73	7.7	.06*

*Significant at the .10 level, 1-tailed test

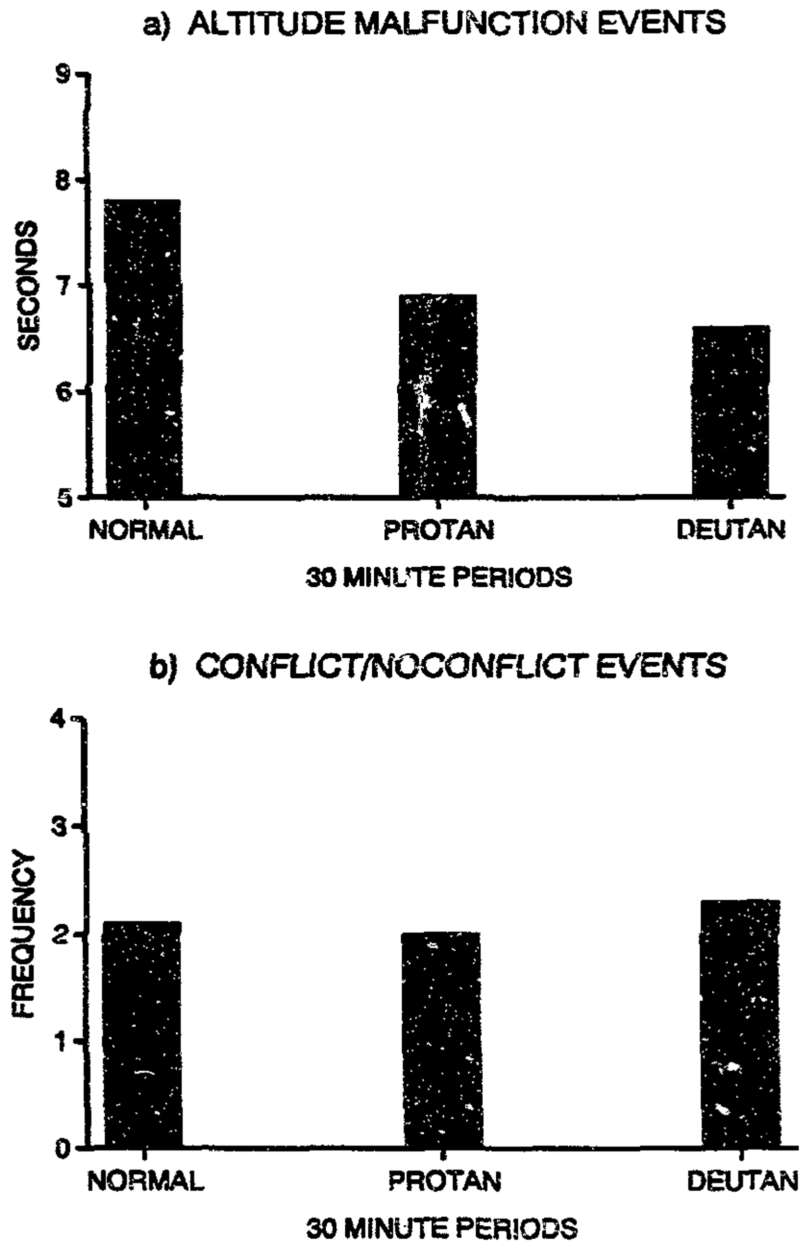

Figure 3

(a) Mean Detection Times for Altitude Malfunction Events for Each Color Vision Group

(b) Mean Frequencies with which Detection Times for Conflict/No Conflict Events Equaled or Exceeded 26s for Each Color Vision Group accord with the experimental hypothesis and can be attributed to the well known reduced sensitivity of protans to red light, in combination with their reduced color discrimination ability as red-green deficients. Although severe deutans have reduced color discrimination, they do not usually have reduced sensitivity. Their performance did not show any reduction compared with normals in the effectiveness of redundant color coding, which was contrary to our prediction. Although this indicates possible beneficial effect of color coding, it is also possible that the 30% greater brightness of red targets may have counteracted the effect of reduced color discrimination in the deutans. If the present display had involved a luminance of red that was equal to or less than green, we could predict that the impairment in detection of red targets by severe protans would be greater, and that the benefit of red highlighting would also have been diminished in severe deutans.

These results demonstrate that the approach of using color always as a redundant cue to ensure performance of color deficients is valuable, but the potential for adverse interaction of color coding with color deficiency must always be considered. These findings also suggest that use of the color red for highlighting may not be appropriate when severe protans are in the user population for the display.

CONCLUSIONS

- The effectiveness of red highlighting used as a redundant cue for attention-getting is diminished in individuals with severe protan color vision deficiency.

- The alerting value of redundant red highlighting was not diminished in deutans, relative to normals, in the present study. Luminance was confounded with color in the present study, however, and may have counteracted the effect of reduced color discrimination in deutans.

- The present findings support the need for further research to evaluate possible differences between individuals in color display effectiveness because of differences in color vision ability.

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