Citation: Birch, J. & Rodriguez-Carmona, M. (2014). Occupational color vision standards: new prospects. Journal of the Optical Society of America A: Optics, Image Science & Vision (JOSA A), 31(4), doi: 10.1364/JOSAA.31.000A55

This is the accepted version of the paper.

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Occupational color vision standards: new prospects

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Received September 30, 2013; revised December 4, 2013; accepted December 8, 2013;
posted December 12, 2013 (Doc. ID 198423); published 0 MONTH 0000

Occupational color vision standards in transport have been implemented for 100 years. A review of these standards has taken place early this century prompted by antidiscrimination laws in the workplace and several transport accidents. The Australian and Canadian Railways have developed new lanterns to address their occupational medical requirements. The Civil Aviation Authority in the UK has adopted the Color Assessment and Diagnosis (CAD) test as the standard for assessing color vision for professional flight crews. The methodology employed using the CAD test ensures that color deficient pilot applicants able to complete the most safety-critical task with the same accuracy as normal trichromats can be accepted for pilot training. This methodology can be extended for setting new color vision standards in other work environments.

OCIS codes: (330.1690) Color; (330.1720) Color vision.
http://dx.doi.org/10.1364/JOSAA.31.00000A

1. INTRODUCTION

Color vision examination was introduced for marine watch keepers and train drivers in the 19th century after two fatal accidents were attributed to inherited red–green (RG) deficiency. Color vision tests and examination procedures were developed and continued almost unchanged throughout the 20th century. However, occupational standards were based on results obtained with differently designed tests and lacked consistency. The aim to adopt uniform standards in international transport was addressed by the Commission Internationale d'Eclairage (CIE) in 2001, and a further review of examination methods was prompted by antidiscrimination laws and two major transport accidents in 1996, near Secaucus, New Jersey, and in 2002 at the Tallahassee airport in Florida.

In 1852 George Wilson estimated that 5.6% of men had inherited RG color deficiency. He was surprised that the prevalence was so high and expressed concern about the safety of rail transport if red and green signals were confused [1,2]. Regulations to restrict the employment of color deficient individuals appeared to be justified after two fatal accidents occurred in 1875. In July that year 10 people were killed when a tug collided with a steam ship off the coast of Norfolk, Virginia. The tug failed to give way and the captain was later found to confuse port and starboard navigation lights. In November two passenger trains collided near the town of Lagerlunda in Sweden. Both drivers and seven passengers were killed. Color deficiency was assumed to be the cause, but there was no evidence that this was the case [3,4]. However, color vision assessment with the Holmgren wool test was introduced for railway employees and recruits for the armed services. This test involved selecting matching shades of wool and was similar to others used in the textile industry [5]. Poor consistency was exposed in the successful legal appeal made by the seaman John Trattles to the British House of Lords in 1897. Trattles passed the Holmgren wool test three times but failed on three other occasions and was refused a first mate's certificate. The test remained in use for a number of years in spite of this adverse publicity [6].

Other occupational physicians considered that color naming was a better method of examination and led to the development of lantern tests. The Edridge–Green lantern (UK), Williams lantern (Canada), and Thomsons lantern (USA) were all manufactured before 1895 and showed several colors, including blue and purple, that were not used in any occupational task [7]. Both the angular subtends and the configuration of lights varied. Some railway companies used both the Holmgren wool test and a lantern test. Painted pseudoisochromatic "vanishing" designs to identify RG deficiency were made in Germany in about 1876 but were liable to fade. These camouflage patterns reproduce colors that RG deficient people confuse and mask perceived lightness differences.

2. DEVELOPMENT OF SCREENING AND OCCUPATIONAL TESTS IN THE 20TH CENTURY

A dedicated occupational lantern for the Merchant Marine Service was approved by the UK Board of Trade in 1913. The BOT lantern displayed nine pairs of red, white, and green signal colors separated horizontally to replicate ship navigation lights at a distance of 2000 yards. The BOT lantern was replaced by the Martin (Marine) lantern in 1939 and again by the Holmes–Wright (H-W) lantern type B in 1974 [8,9]. These lanterns had the same basic design but had improved mechanical construction and modern light sources. The aim was to provide continuity rather than change the selection criteria. A second version of the Martin lantern was produced for rail transport in 1943 that included a yellow test color [10]. An occupational lantern, based on the design of the BOT lantern, was developed for the Royal Canadian Navy in 1943 [11].

The Ishihara pseudoisochromatic test (1917) utilized new printing techniques and contained both "transformation" and "vanishing" designs for screening and classification.

The test has been reprinted many times and is accepted worldwide as the most efficient clinical screening test for inherited RG deficiency [12]. Background knowledge of the Ishihara test is needed in order to ensure the results are interpreted correctly, so that 100% specificity and close to 97% sensitivity are achieved.

In 1881 John William Strutt, second Baron Rayleigh, showed that measurement of the proportions of red and green wavelengths (670 and 546 nm) needed to match an intermediate yellow (589 nm) to distinguish normal and abnormal RG vision. The characteristics of a Rayleigh match and the range of matching red/green mixture ratios determines the class and severity of color deficiency [13]. Dichromats (protanopes and deuteranopes) are distinguished from anomalous trichromats and always have severe deficiency. Severity varies in a continuous range from minimal to severe in protanomalous and deuteranomalous trichromatism according to the expression of X chromosome genes that program photopigments with different peak wavelength sensitivities [14]. A compact instrument to measure the characteristics of a Rayleigh match was designed by Nagel and manufactured in Germany in 1907 and remains the accepted "gold standard" reference test for RG deficiency.

Large population surveys with the Ishihara plates and Nagel anomaloscope show that 8% of men have some type of inherited RG deficiency [15]. Approximately 6% have deutan deficiency and 2% have protan deficiency, which is characterized by reduced long wavelength sensitivity and is a particular handicap in occupations that rely on the prompt recognition of red signals and safety warnings. All color deficient individuals see fewer colors in the environment and confuse colors that are easily distinguished by normal trichromats. Detailed measurement of protan and deutan color confusions was made by Wright and his coworkers between 1930 and 1945 and is reproduced in isochromatic zones in the CIE chromaticity diagram 1931 [16,17]. Colors specified by x, y chromaticity coordinates within an isochromatic zone look the same if there is no perceived luminance contrast. The chromaticities of industrial color reference standards, safety codes, and international signal lights are specified in the same system of measurement providing a guide to the discrimination ability of a color deficient person.

In 1919 it was decided that aircraft pilots must be able to distinguish colored lights used in air navigation [2]. The correct naming of red and green flares, which indicated permission to land, was probably all that was required. The Martin lantern was subsequently used by the Civil Aviation Authority (CAA) and the UK armed services and was eventually replaced by the H-W type A [9]. The H-W type A displays specified red, green, and white lights, which are within the revised range of approved chromaticities recommended by the CIE in 2001 [18]. The H-W type A is an efficient screening test for RG deficiency if the nine color pairs are shown three times [19]. The H-W type A is still used today by the armed services, and the type B for the Merchant Marine services in the UK. The Beyne lantern (France) was manufactured in 1950 and displays five single colors, including blue and yellow, derived from narrow wavelength bands. The Spectrolux lantern (Switzerland) came into service in the 1980s for use in aviation and displays 12 pairs of red, green, and white signal lights that have the same chromaticities as airport navigation lights [20]. The chromaticities, the configuration of the lights, and the angular subtends are different for each of these lanterns. The examination procedures also vary.

3. GRADING TESTS FOR OCCUPATIONAL SELECTION

"Grading" tests, intended to identify people with moderate/severe deficiency likely to have significant problems with color in the work environment, were introduced in the USA after 1945. These were secondary tests only given to people who had failed a screening test. The Farnsworth lantern (Falant) was originally developed for use in the United States Navy but was subsequently adopted by all the armed services and by commercial aviation in the USA [21]. The Falant displays nine pairs of red, yellow–green, and yellowish-white lights that have x, y chromaticity coordinates within a common protan/deutan isochromatic zone. A pass can be obtained in two ways: if no error is made on the first run of nine color pairs (the examination is then discontinued), or, alternatively, if an error is made on the first run, two more runs are shown and a pass is obtained if only two errors are made [22].

The Farnsworth D15 (D15) test (1947) and the American Optical Company (Hardy, Rand and Rittler) pseudoisochromatic (HRR) test (1954) were intended to be used in industry and have some capability for identifying yellow/blue color deficiency. The grading capability of the HRR test is based on neutral color confusions embedded on a background matrix of gray dots in a series of designs with ranked color different steps. Two different pass criteria have been used with the D15 test; (i) approximately 40% of RG deficient people pass if a circular results diagram is required and (ii) 60% are successful if two (errors) lines across the results diagram are allowed [23]. Protans are more successful than deutans on the D15 because performance is aided by perceived luminance contrast. Although the Falant and the D15 have similar aims, a pass on the D15 does not ensure that a pass will be achieved on the Falant [24,25].

In 2001 the CIE commissioned a review of color vision examination procedures used in international transport with the aim of producing uniform standards for employment [26]. It was proposed that new color vision requirements should be based on results obtained with the Ishihara test, the D15, and a lantern test. The recommended lanterns are the Beyne lantern (or TriTest 13), the Falant (or Optec 900), and H-W lantern types A and B. The Nagel anomaloscope or the Medmont test (or equivalent) are recommended to classify protans if required. The CIE recommendations are logical and well presented, but consistent standards cannot be realized because very different fail rates are obtained with the recommended lanterns. For example, about 30% of color deficient people pass the Falant, but only 15% pass the H-W type A if the same criteria are applied [27]. The results also lack internal consistency in that a person who passes at the first stage of the examination may not achieve a pass at the second stage if the examination is continued [28]. The Spectrolux lantern was not mentioned in the CIE report but is approved as a secondary test, in common with the H-W type A and Beyne lanterns, for Joint Aviation Requirements (JAR) by the Joint Aviation Authorities (JAA) [20].

4. NEW PROSPECTS

Laws that limit discrimination against disabled or disadvantaged people in the workplace were passed in most developed countries between 2002 and 2005. The UK Disability Discrimination Act (2004) particularly placed the onus on employers to modify important or safety-critical color tasks to enable color deficient people to work as normal [29]. Refusal of employment remained lawful if this could not be done.

The need for change was emphasized after two transport accidents, attributed to color deficiency, occurring in 1996 and 2002. In 1996 two passenger trains collided head-on near Secaucus, New Jersey. Three people were killed, including one of the drivers, and 69 people were injured. The cost of the damage was estimated at more than $3.3 million. The deceased driver was known to have acquired color deficiency due to diabetic eye disease [30]. In 2002 a FedEx Boeing 737 landed in trees short of the runway at Tallahassee Airport, Florida, and was destroyed by fire. All three crew members were seriously injured [31]. The first officer, piloting the aircraft, had severe inherited RG deficiency but had passed an examination with the Falant lantern. The official accident report ordered a review of color vision examination procedures and recommended that the Falant be discontinued. Poor interpretation of the Precision Approach Path Indicator (PAPI) code was considered to be the primary cause of the accident, and the later study by Cole and Maddock (2008) showed that 10 of 52 RG deficient subjects that passed the Falant could not perform a simulated PAPI task as normal trichromats [32].

A review of occupational medical requirements in Australia was ordered after the Waterfall train crash in 2003. The cause of the accident was the sudden incapacitation of the driver following a cardiac arrest [33]. Equal opportunity laws in both Australia and Canada require color vision standards to be implemented with a dedicated test directly linked to the visual task needed in the occupation; see Table 1. As a result two new occupational lanterns for rail transport were developed in these countries. Both the Australian RailCorp or "LED" lantern and the Canadian lantern (CNLAN) reproduce the chromaticities and configuration of track side signals and include yellow/amber as a test color [33,34]. Only failure to see a red light or name it incorrectly results in failure of the RailCorp lantern. This criterion passes a higher percentage of color deficient subjects than the Falant and about 50% of subjects that pass the D15. The CNLAN presents 22 triplicates of red, yellow, and green lights. This is a difficult discrimination task for normal trichromats, and up to five errors must be allowed as a pass. The pass level is therefore very similar to that obtained with the H-W type A. Only deutans with minimal deficiency are likely to be successful. Fewer errors are made if the normal test distance (4.6 m) is reduced by 50%. In this case the majority of deuteranomalous trichromats and some protanomalous trichromats obtain a pass [35]. It is suggested that these applicants could be employed as rail-yard shunters where signals are observed at short distances and subtend a larger visual angle.

Investigation of acquired color deficiency performed on high-resolution color calibrated visual display units has provided new insights into the characteristics of this type of color vision loss [36–39]. The Color Assessment and Diagnosis (CAD) test was accepted by the CAA (UK) to implement a new color vision standard for commercial airline pilots in 2009 [40]. The CAD test presents a moving target of precise chromaticity and saturation embedded in a background of dynamic luminance contrast noise that masks the perception of any luminance contrast isolating the use of color. The target moves along one of four diagonal directions, and the subject presses a button to indicate the direction of motion. Thresholds that define RG and yellow–blue (YB) sensitivity within isochromatic zones are plotted as x, y chromaticity coordinates in the 1931 CIE chromaticity diagram. The results classify protan and deutan deficiency and estimate the severity of the color vision loss accurately [40–42]. The results are in close agreement with the characteristics of the Rayleigh match obtained with the Nagel anomaloscope and confirm genetic data that show that the mildest protanomalous trichromats have more severe deficiency than deuteranomalous trichromats [14]. The median threshold value, obtained for 250 normal trichromats, is designated as 1 standard normal CAD unit (1 SN unit) [41]. Threshold values obtained by color deficient subjects are recorded as the number of SN units. The first stage of the investigation was to compare the results obtained by normal trichromats and a representative group of color deficient subjects on a simulation of the PAPI discrimination task. The PAPI system consists of four horizontal lights at the side of the runway viewed by all pilots on a landing approach. The lights can be any combination of red or white. Commercial airline pilots must be able to distinguish the number of red and white lights at a distance of 4 miles (5.5 km). The correct approach path is shown by two white and two red lights and must be maintained until the aircraft has landed. A precise reconstruction of the PAPI lights display was made in the laboratory at City University London and viewed by 64 normal trichromats and 111 male color deficient subjects (40 protans and 71 deutans) identified with the Ishihara plates and classified with the Nagel anomaloscope. The age of the subjects ranged from 15 to 55 years (mean age 30.2 years). The five possible combinations of red and white lights were viewed 12 times in a random sequence (60 presentations) with each subject reporting the number of red lights seen following an auditory cue at the end of a 3 s viewing time. The percentage of correct answers was calculated for each subject and compared with the RG threshold measured with the CAD test.

Individual CAD thresholds are shown in Fig. 1. RG thresholds obtained by normal trichromats are closely grouped and

Table 1. Requirements for Setting New Occupational Color Vision Standards

1. Knowledge of the requirements of the occupation and awareness of the consequences of error or slow working.
2. Identification of the most difficult safety-critical task in the occupation.
3. Knowledge of the characteristics of different types of inherited RG color deficiency.
4. Assessment of the ability of a color deficient person to complete the most safety-critical task with the same accuracy as a normal trichromat.
5. Implementation of a new standard based on results obtained with a validated objective test that ensures that individuals with potentially dangerous severe RG deficiency are excluded.

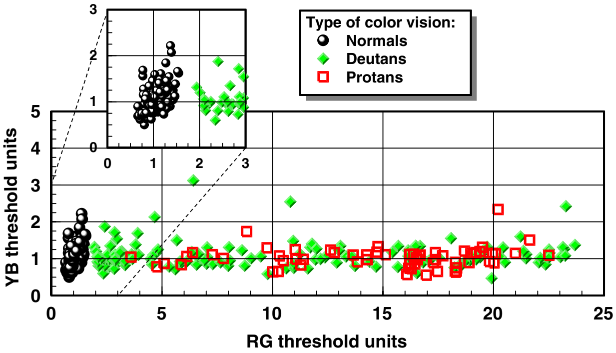

Fig. 1. Graph showing red–green (RG) and yellow–blue (YB) thresholds expressed in CAD standard normal units for 450 subjects. Reproduced from [40], Fig. 12. The spread of data along the abscissa illustrates the large variation that exists amongst subjects with deutan- and protan-like deficiencies. The results show that the RG thresholds vary almost continuously from very close to "normal" to extreme values that can be 25 times larger than the standard normal threshold. The YB thresholds, on the other hand, vary very little as expected in the absence of YB loss or acquired deficiency.

are clearly separated from the thresholds of deuteranomalous trichromats with minimal deficiency showing that the CAD test is an efficient screening test (see inset). A comparison with the PAPI results found that protans with RG CAD thresholds less that 12 SN units and deutans with CAD thresholds less than 6 units performed the PAPI test as well as normal trichromats and can safety be allowed to begin pilot training [40]. However, a small number of deutans and protans with RG CAD thresholds larger than these limits are able to pass the PAPI test. Ensuring color deficient subjects have RG thresholds within these limits guarantees that all subjects have adequate overall chromatic sensitivity and are not disadvantaged in other, less safety-critical, visual tasks that involve color discrimination [40]. The proposed pass/fail limits for deutans and protans have replaced use of the H-W lantern type A. This outcome particularly favors minimal/slight deuteranomalous trichromats that would have failed an examination with the H-W lantern type A and been rejected.

The cone contrast test is also performed on a high-resolution color calibrated display and is being considered as a possible replacement for the Falant [43]. The visual task is similar to that of the HRR test. Ten single uppercase letters are presented at decreasing levels of contrast and must be identified verbally. The selected chromaticities are derived from L, M, and S spectral functions determined by Smith and Pokorny (1975). Preliminary results show that the test is more sensitive than the Dvorine pseudoisochromatic test for screening but the predictive value of the quantitative results has yet to be determined in the occupational environment [43].

5. DISCUSSION: FUTURE PROSPECTS

Color vision standards in transport have been implemented with the use of the Ishihara test and a lantern throughout the 20th century. The former was used to identify RG deficiency, and the latter to determine occupational suitability. Lanterns manufactured in the second half of the 20th century, listed in the CIE report, are robust and remain in service [26]. New versions of the Falant and the Beyne lantern are also available. Good understanding is required for optimum use of the Ishihara test [12]. However, there are examples of national and international advisory committees setting inappropriate pass/fail criteria for both the Ishihara plates and the Nagel anomaloscope that have resulted in a large number of normal trichromats having to complete a lantern test unnecessarily [20,35]. It is clear that uniform international occupational standards cannot be achieved with differently designed lanterns. New dedicated lanterns exclusively for rail networks in Canada and Australia have addressed this problem on a national basis. Nevertheless, naming is not an ideal visual task for assessing discrimination ability, and a single misnamed color remains the difference between pass and fail because color deficient individuals guess or attempt to use perceived luminance contrast as an aid. Highly motivated applicants are determined "to beat the test," and some demand a second chance [20].

It is appropriate to consider the application of new technology to resolve the present inconsistencies. There are considerable advantages in setting new evidence-based color vision standards using a single accredited test linked to satisfactory completion of the most safety color critical task. A computerized assessment procedure eliminates examiner variance, ensures that the same pass/fail decisions are made in all examination centers, and is fairer to applicants. The CAD test has already been accepted by 64 airline companies worldwide that use the medical examination and professional pilot licensing facilities offered by the CAA and has been accepted as an approved screening test by the National Air Traffic Society (NATS) [44]. NATS is the leading provider of air traffic control services in the UK and in 30 countries worldwide. An investigation to determine the most safety-critical task on the London Underground has been made, and the CAD test is being considered as a replacement for the Ishihara test for screening. Following the methodology outlined in Table 1, similar evidence-based criteria can be applied for setting new standards in other work environments.

ACKNOWLEDGMENTS

We thank our colleagues John Barbur and Alistair Harlow for useful discussions and technical support of some of the tests described in this paper. The majority of the data reported here were obtained in studies supported by the CAA (UK). Significant contribution to these studies was also made by Transport for London and the Federal Aviation Administration (USA).

REFERENCES

1. G. Wilson, *Researches on Color Blindness: With a Supplement on Danger Attending the Present System of Railway and Marine Color Signals* (Sutherland and Knox, 1855).
2. A. J. Vingrys and B. L. Cole, "Origins of color vision standards within the transport industry," Ophthalmic Physiolog. Opt. **6**, 369–375 (1986).
3. A. J. Vingrys and B. L. Cole, "Are color vision standards justified in the transport industry?" Ophthalmic Physiolog. Opt. **8**, 257–274 (1988).
4. J. D. Mollon and L. R. Cavonius, "The Lagerlunda collision and the introduction of color vision testing," Surv. Ophthalmol. **57**, 178–194 (2012).
5. E. Murray, "The evolution of color vision tests," J. Opt. Soc. Am. **33**, 316–334 (1943).
6. H. Topley, "Sight testing for the Merchant Navy," Br. J. Physiol. Opt. **16**, 36–46 (1959).
7. B. L. Cole and A. L. Vingrys, "A survey and evaluation of lantern tests of color vision," Am. J. Optom. Physiol. Opt. **59**, 346–374 (1982).

8. L. C. Martin, “A standardized Lantern for testing color vision,” Br. J. Ophthalmol. **23**, 1–20 (1939).
9. J. G. Holmes and W. D. Wright, “A new color-perception lantern,” Color Res. Appl. **7**, 82–88 (1982).
10. L. C. Martin, “A standardized color-vision testing lantern (II) transport type,” Br. J. Ophthalmol. **27**, 255–259 (1943).
11. D. Y. Solandt and C. H. Best, “The Royal Canadian navy color vision test lantern,” Can. Med. Assoc. J. **48**, 18–21 (1943).
12. J. Birch, “Efficiency of the Ishihara plates for identifying red-green color deficiency,” Ophthalmic Physiolog. Opt. **17**, 403–408 (1997).
13. L. Rayleigh, “Experiments on color,” Nature **25**, 64–66 (1881).
14. S. S. Deeb, “The molecular basis of variation in human color vision,” Clin. Genet. **67**, 369–377 (2005).
15. J. Birch, “Worldwide prevalence of red-green color deficiency,” J. Opt. Soc. Am. A **29**, 313–320 (2012).
16. F. H. G. Pitt, “Characteristics of dichromatic vision,” Medical Research Council Special Report Series No. 200 (HMSO, London, 1935).
17. W. D. Wright, *Researches in Normal and Defective Color Vision* (Henry Kimpton, 1946).
18. CIE, “Colours of light signals,” Report No. S004 (Commission Internationale d’Eclairage, 2001).
19. J. Birch, “Performance of red-green color deficient subjects on the Holmes-Wright lantern (type A) in photopic viewing,” Aviat. Space Environ. Med. **70**, 897–901 (1999).
20. T. J. Squire, M. L. Rodriguez-Carmona, A. D. B. Evans, and J. L. Barbur, “Color vision tests in aviation: comparison of the anomaloscope and three lantern types,” Aviat. Space Environ. Med. **76**, 421–429 (2005).
21. D. Farnsworth and P. Foreman, “Development and trial of the New London Navy Lantern as selection test for serviceable colour vision,” Report No. 105 (US Naval Submarine Base Medical Research Lab, New London, Connecticut, 1946).
22. J. Birch and S. J. Dain, “Performance of red-green color deficient people on the Farnsworth lantern (Falant),” Aviat. Space Environ. Med. **70**, 62–67 (1999).
23. J. Birch, “Pass rates for the Farnsworth D15 color vision test,” Ophthalmic Physiolog. Opt. **28**, 259–264 (2008).
24. B. L. Cole and A. J. Vingrys, “Who fails lantern tests?” Doc. Ophthalmol. **55**, 157–162 (1983).
25. B. L. Cole and J. D. Maddock, “Can clinical color vision tests predict the results on the Farnsworth lantern?” Vis. Res. **38**, 3483–3485 (1998).
26. CIE, “International recommendations for color vision requirements in transport,” Report No. 143 (Commission Internationale d’Eclairage, 2001).
27. A. J. Vingrys and B. L. Cole, “Validation of the Holmes–Wright lanterns for testing color vision,” Ophthalmic Physiolog. Opt. **3**, 137–152 (1983).
28. J. Birch, “Performance of color deficient people on the Holmes–Wright lantern (type A): consistency of occupational color vision standards in aviation,” Ophthalmic Physiolog. Opt. **28**, 253–258 (2008).
29. Health, and Safety Executive, Color Vision Examination: A Guide for Occupational Health Providers, HSE Guidance Note MS7, 3rd ed. (2005).
30. National Transport Safety Board Washington DC R-97-1 and -2 (NTSB, 1997).
31. National Transport Safety Board Washington DC R-04-46 and -47 (NTSB, 2004).
32. B. L. Cole and J. D. Maddock, “Color vision testing with the Farnsworth lantern and ability to identify approach-path signal lights,” Aviat. Space Environ. Med. **79**, 585–590 (2008).
33. A. Casolin, P. L. Katalinic, G. S. Yuen, and S. J. Dain, “The RailCorp lantern test,” Occup. Med. **61**, 171–177 (2011).
34. J. K. Hovis and D. Oliphant, “A lantern color vision test for the rail industry,” Am. J. Ind. Med. **38**, 681–696 (2000).
35. J. K. Hovis and S. Ramaswamy, “The effect of distance on the CN lantern results,” Vis. Neurosci. **23**, 675–679 (2006).
36. F. G. Rauscher, G. Plant, and J. L. Barbur, “Patterns of color vision loss that result from damage to pre-striate and extra-striate visual pathways,” Investig. Ophthalmol. Vis. Sci. **47**, 2669 (2006).
37. M. O’Neill-Biba, S. Sivaprasad, M. Rodriguez-Carmona, J. E. Wolf, and J. L. Barbur, “Loss of chromatic sensitivity in AMD and diabetes: a comparative study,” Ophthalmic Physiolog. Opt. **30**, 705–716 (2010).
38. D. F. Ventura, M. Gualtieri, A. G. Oliveira, M. F. Costa, P. Quiros, F. Sadun, A. M. de Negri, S. R. Salomão, A. Berezovsky, J. Sherman, A. A. Sadun, and V. Carelli, “Male prevalence of acquired color vision defects in asymptomatic carriers of Leber’s inherited optic neuropathy,” Investig. Ophthalmol. Vis. Sci. **48**, 2362–2370 (2007).
39. D. F. Ventura, A. L. Simoes, S. Tomaz, M. F. Costa, M. Lago, M. T. Costa, L. H. Canto-Pereira, J. M. de Souza, M. A. Faria, and L. C. Silveira, “Color vision and contrast sensitivity losses of mercury intoxicated industrial workers in Brazil,” Environ. Toxicol. Pharmacol. **19**, 523–529 (2005).
40. CAA, “Minimum color vision requirements for professional flight crew: recommendations for new color vision standards,” CAA paper 2009/4 (2009). http://www.caa.co.uk/docs/33/200904.pdf.
41. M. Rodriguez-Carmona, A. Harlow, G. Walker, and J. L. Barbur, “The variability of normal trichromatic vision and the establishment of the ‘normal’ range,” in *Proceedings of the 10th Congress of International Color Association*, Granada, Spain (AIC, 2005), pp. 979–982.
42. M. Rodriguez-Carmona, M. O’Neill-Biba, and J. L. Barbur, “Assessing the severity of color vision loss with implications for aviation and other occupational environments,” Aviat. Space Environ. Med. **83**, 19–29 (2012).
43. J. Rabin, J. Gooch, and D. Ivan, “Rapid quantification of color vision: the cone contrast test,” Investig. Ophthalmol. Vis. Sci. **52**, 816–820 (2011).
44. Eligibility—NATS/A global leader in Air Traffic Control (2013), http://www.nats.co.uk/careers/atc/how-to-apply/eligibility/.

Queries

1. AU: Is any new references need to be added in the references list for “Cole and Maddock (2008)” and “Smith and Pokorny (1975)” in this paper?