Institution: City, University of London		
Unit of Assessment: 03 Allied Health Professions, Dentistry, Nursing and Pharmacy		
Title of case study: Colour vision testing in safety critical occupations; improving safety and equity		
Period when the underpinning research was undertaken: 2010 – ongoing		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof John Barbur	Professor of Optics and Visual Science	1981 – present
Dr Marisa Rodriguez-Carmona	Research Assistant / Lecturer	2005 – present
Period when the claimed impact occurred: August 2013 – ongoing		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Congenital colour vision deficiency affects approximately 2,638,258 males and 135,274 females in the UK. New grading scales for colour vision assessment, based on the use of a novel colour vision screener with 100% test efficiency followed by the Colour Assessment and Diagnosis (CAD) test, have been developed. The rapid colour vision screener ensures that only 6% of applicants require the full CAD test, greatly improving the efficiency of colour vision testing. These developments have decreased variability and enabled the introduction of safer and fairer pass/fail limits within visually-demanding and safety-critical occupations. The tests and associated grading scales have been adopted worldwide as an accurate and efficient system for colour vision assessment by transport authorities, government organisations and industry.

2. Underpinning research

The prevalence of congenital colour vision deficiency (CCVD) is approximately 8% for males and 0.4% for females. The severity of CCVD varies from near normal sensitivity to complete absence of colour vision. In addition, diseases of the eye and systemic diseases such as diabetes can cause acquired loss of colour vision, particularly in older subjects. Colour vision yields significant advantages in many visual tasks and, in some occupations, the normal processing and correct interpretation of colour signals is vital for safety [3.1; 3.2].

Colour vision assessment currently relies on conventional tests such as Ishihara plates and the Farnsworth Munsell D-15. Our research has demonstrated that these tests fail to isolate uniquely either Red/Green (RG) or Yellow/Blue (YB) colour signals and are not able to eliminate all other cues an applicant could use to pass the test [3.3]. In addition, these tests do not quantify reliably the severity of colour vision loss, and they fail to identify accurately the applicant's class of colour vision or the presence of acquired loss [3.2].

In the largest study of its type, *Barbur* and colleagues examined the sensitivity and specificity of commonly used, conventional colour vision tests including the Farnsworth-Munsell D15, Ishihara plates, Holmes-Wright lanterns and the Nagel anomaloscope [3.3; 3.4]. In the study, 1,830 participants, (350 normal trichromats, 1,012 deuteranopes, 465 protanopes and 3 tritanopes), had a full colour vision assessment using the CAD test as well as conventional colour vision tests. None of the conventional tests came anywhere close to achieving 100% sensitivity and specificity with some tests and protocols passing as many as 55% of colour deficient subjects [3.4]. The best performing conventional test was the 38 plate Ishihara; with no errors allowed, almost all CCVD subjects failed, but 19.4% of normal trichromats also failed resulting in very poor specificity [3.4]. As a result of this research, and commissioned reports, which carried out a detailed analysis of the outcome of current practices within the Electrical Contractors Industry, the Police and Fire

Services, the Maritime Coastguard Agency and the Defence Medical Services, the need to develop a rapid and accurate colour vision screener became apparent.

The CAD test, initially developed for research studies into colour vision, overcomes the limitations of conventional tests but the full RG and YB colour vision assessment takes up to 15 minutes to complete and the test runs on expensive, fully-calibrated visual displays limiting its availability. If screening for the presence of congenital or/and acquired colour deficiency could be carried out rapidly on home computers with high sensitivity and specificity, only approximately 6% of applicants tested would require a full colour vision assessment on advanced tests such as CAD [3.5]. A 'two-step' protocol based on screening followed by the CAD test therefore has many advantages, but requires the availability of an inexpensive and rapid screener with close to 100% test efficiency [3.5].

The development of the colour vision screener (CVS) test was based on important findings that have emerged from our research studies during the last decade: (i) the establishment of reliable upper-normal threshold limits as a function of age for both RG and YB colour vision [3.6]; (ii) accurate assessments of intra- and inter-subject variability [3.5]; (iii) the discovery of a large (approximately two-fold difference) in RG chromatic sensitivity between the least-affected deuteranopes and protanopes; (iv) the realisation that the least-sensitive normal trichromats and the least-affected deuteranopes with overlapping thresholds at the upper normal limit have mean thresholds that are well below and above the upper normal age limits, respectively [3.5]. These findings made it possible to produce a statistical model to optimise the parameters of the CVS test and to predict the expected sensitivity and specificity. The experimental findings confirm model predictions and reveal 100% CVS test efficiency [3.5].

In addition to the research studies needed to develop the screener, the large database of colour deficient subjects examined at City, University of London has enabled us to predict accurately the outcomes of the most important, multi-test protocols in current use [3.2; 3.4] and to demonstrate the advantages of the two-step protocol over current practices [3.5]. As a result of the two-step protocol, the assessment of colour vision becomes more accurate, more efficient and simpler to carry out. A single colour assessment test can be used to establish the applicant's severity of colour vision loss, which can range from 'supernormal' (CV0) for the most stringent, colour-demanding tasks, to 'severe colour deficiency' (CV5), when R/G colour vision is either absent or extremely weak.

3. References to the research

[3.1] Barbur JL, Rodriguez-Carmona, M., Hickey, J., Evans, S., Chorley, A. Analysis of European Colour Vision Certification Requirements for Air Traffic Control Officers. London, UK: CAA (UK) Report, CAP 1429; 2016. pp 1-76. http://publicapps.caa.co.uk/docs/33/CAP%201429%20OCT16.pdf

[3.2] Barbur JL, Rodriguez-Carmona M. Colour vision requirements in visually demanding occupations. British medical bulletin. 2017;122(1):51-77. https://doi.org/10.1093/bmb/ldx007

[3.3] Evans BE, Rodriguez-Carmona M, Barbur JL. Color vision assessment-1: Visual signals that affect the results of the Farnsworth D-15 test. Color Research & Application. 2021;46(1):7-20. (First published 25 November 2020). https://doi.org/10.1002/col.22596

[3.4] Rodriguez-Carmona M, Evans BE, Barbur JL. Color vision assessment-2: Color assessment outcomes using single and multi-test protocols. Color Research & Application. 2021;46(1):21-32. (First published 30 November 2020). https://doi.org/10.1002/col.22598

[3.5] Barbur JL, Rodriguez-Carmona M, Evans BE. Color vision assessment-3. An efficient, two-step, color assessment protocol. Color Research & Application. 2021;46(1):33-45. (First published 25 November 2020). https://doi.org/10.1002/col.22599

[3.6] Barbur, J. L. and Rodriguez-Carmona, M. Color vision changes in normal aging. In: Elliott, A. J., Fairchild, M. D. and Franklin, A. (Eds.), Handbook of Color Psychology. 2016. pp 180-196. Cambridge: Cambridge University Press. (Available from https://openaccess.city.ac.uk/id/eprint/12513/ accessed 21 March 2021)

All outputs were published in prestigious academic journals that apply a rigorous peer-review process prior to acceptance of papers. The outputs were supported by grants from: CAA (UK), 'Minimum Colour Vision Requirements for Air Traffic Controllers', *Barbur* PI, 2012-2015, GBP43,400; The Colt Foundation, 'Assessing the severity of colour vision loss in occupational environments', *Barbur* PI, 2012-2015, GBP107,979 and 'Development and validation of a colour vision screener test for use in visually-demanding occupations and primary healthcare', *Barbur* PI, 2017-2020, GBP87,497.

4. Details of the impact

Impact on Public Policy and Services

Our research has led to the development of the rapid CVS test and the establishment of new CV# grading scales for quantifying the severity of RG and YB colour vision loss. The CVS test and associated protocols based on the CAD test are highly reproducible. Their adoption internationally has led to reduced variability in colour vision assessment and safer working environments by eliminating those applicants with severe deficiency who passed conventional protocols. They have also resulted in greater fairness for those less severe applicants who failed conventional tests, but pass the protocols based on the CAD test and are therefore able to carry out colour-related, safety-critical tasks with the same accuracy as normal trichromats [3.2].

The three-year project 'Analysis of European colour vision certification requirements for Air Traffic Control (ATC) officers' led to a change in policy by the CAA (UK) with the adoption of the CV2 grade for operators [5.1]. In 2019, the European Aviation and Space Agency (EASA) decided to adopt the CAD test and the stricter CV1 grade for Air Traffic Controllers (ATC). Since then all EASA member states require ATC operators to have normal trichromatic colour vision [5.2]. Neither the Ishihara test nor the Nagel anomaloscope assess YB colour deficiency and so the CAD test has become the default standard for ATCs. The colour vision research carried out at City, University of London has therefore had an impact on all EU air travel with the CV1 grade colour vision requirements applying to all 17,000 ATC officers improving the safety for 1,106M air passengers per year (EuroStat, 2018) [5.3].

Our research has also led to a report on colour vision assessment commissioned by the UK Maritime and Coastguard Agency (MCA) [5.4]. This report has led to significant impact, both in the UK and abroad. MCA is responsible for legislation and guidance on maritime matters and provides safety certification to seafarers. The study analysed the statistical outcomes of colour vision testing protocols previously used by the MCA using the City data set, which at the time of the study included 1,363 participants. The report identified the CV2 grading scale as a safer, simpler to administer, less variable and fairer colour vision requirement for lookout officers [5.4]. In 2018, MCA changed its policy and practice by adopting the CV2 grade and establishing guidelines alongside setting up four authorised colour vision test centres in the UK equipped with the CAD test [5.5]. Following the introduction of the new protocol, the number of appeals and retests, which were common in the past, reduced significantly. The adoption of the CV2 grade for colour vision affects the safety of everyone using UK waters including approximately 120,000 vessels and 20,700,000 international passengers arriving at UK ports in 2019 according to UK Government statistics.

[Text removed for publication] [5.6].

The CAD test and new CV# grading scales have also been adopted by industry for occupations where colour vision is important. For example, the CV3 grade was adopted by the Joint Industry Board (JIB) in 2017 for electrical contractors [5.7]. Use of the CV3 grade triples the number of applicants with CCVD who meet the JIB requirements. Applicants with CCVD who pass at the CV3 limit are 3-times *less* severe in terms of their RG colour vision loss than the most severe applicants who pass the current protocol (Fig. 10b in [3.2]). This results in both fairer and safer access to the electrical professions. In addition, the CAD test and CV# grading scales also assess YB colour vision, which is essential for detection of acquired loss.

Impact on Commerce and the Economy

In addition to the impact on policy and practice, the CAD test has been made commercially available through City Occupational Ltd (COL). COL is a spinout company of City, University of

London, which was established in August 2013 to develop, manufacture and distribute a number of tests for use in research, primary healthcare and visually demanding occupations. City, University of London licensed the Intellectual Property to COL and as a result, the company has developed and sold CAD systems to vision research institutes, universities, aviation authorities, eye clinics, defence medical centres, authorised medical examiners, vision scientists and optometrists worldwide [5.8]. For example, a multi-centre gene therapy trial for achromatopsia has chosen our colour vision tests, alongside other advanced vision tests underpinned by our research, as outcome measures [5.9].

[Text removed for publication]

5. Sources to corroborate the impact

[5.1] UK CAA Policy Statement: Colour Vision in Air traffic Controllers. EU Class 3 ATCO Colour vision Policy V1.1. July 2017. p1. (Available from https://www.caa.co.uk/WorkArea/DownloadAsset.aspx?id=4294985496 accessed 20 March 2021)

[5.2] EASA: Easy Access Rules for Air Traffic Controllers Licensing and Certification (Regulation (EU) 2015/340). December 2019. P208. (Available from https://www.easa.europa.eu/sites/default/files/dfu/Easy_Access_Rules_for_Air_Traffic_Controllers_Licensing_and_Certificatio....pdf accessed 20 March 2021)

[5.3] Corroboration can be provided by the Secretary General of the International Academy of Aviation and Space Medicine who is also the former chief medical officer of the Civil Aviation Authority and International Civil Aviation Organisation.

[5.4] Colour vision assessment for maritime navigational lookout: review for UK Maritime and Coastguard Agency' (July 2015) (Available from https://www.gov.uk/government/publications/colour-vision-assessment-for-maritime-navigation-lookout accessed 20 March 2021)

[5.5] UK Maritime and Coastguard Agency MSN 1886 (M+F): Includes Appointment of Approved Doctors and Medical and Eyesight Standards (December 2018). Pp5-6 and Annex B. (Available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/876405/MIN_564.pdf accessed 20 March 2021)

[5.6] [Text removed for publication]

[5.7] Joint Industry Board Handbook 2017, Section 8 JIB Training Services, Appendix A, p198. (Available from https://www.jib.org.uk/documents/content/files/2017-Apprenticeship-Scheme.pdf accessed 21 March 2021)

[5.8] [Text removed for publication].

[5.9] Testimonial from AGTC confirming the use of colour vision and other Advanced Vision and Optometric Tests in gene therapy trials for achromatopsia.