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ORIGINAL ARTICLE

Impact of blur on clinical and occupational colour vision test results

Leticia Álvaro[1] | **Monika A. Formankiewicz**[2] | **Sarah J. Waugh**[3]

[1]Departamento Psicología Experimental, Procesos Cognitivos y Logopedia, Universidad Complutense de Madrid, Pozuelo de Alarcón, Spain

[2]Vision and Hearing Sciences Research Centre, School of Psychology and Sports Science, Anglia Ruskin University, Cambridge, UK

[3]Centre for Vision across the Life Span, School of Applied Sciences, University of Huddersfield, Huddersfield, UK

Correspondence
Leticia Álvaro, Departamento Psicología Experimental, Procesos Cognitivos y Logopedia, Universidad Complutense de Madrid, Pozuelo de Alarcón, Spain.
Email: lalvaro@ucm.es

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Abstract

Purpose: To evaluate whether colour vision normal (CVN) adults pass two Fletcher–Evans (CAM) lantern tests and to investigate the impact of imposed blur on Ishihara, CAM lantern and computerised colour discrimination test (colour assessment and diagnosis test [CAD] and Cambridge colour test [CCT]) results.

Methods: In a pilot experiment, 20 (16 CVN and 4 colour vision deficient [CVD]) participants with normal VA were tested with the CAM lantern. In the main experiment, the impact of imposed dioptric blur (up to +8.00 D) on visual acuity and the Ishihara test, CAM lantern, CAD and CCT was assessed for 15 CVN participants.

Results: CVN participants can fail the CAM lantern, with specificity of 81.25% (aviation mode) and 75% (clinical mode), despite following the test requirements of participants having at least 0.18 logMAR (6/9) in the better eye. With blur, test accuracy was affected. As expected, significant detrimental effects of blur on test results were found for logMAR VA and CAM lantern (aviation) with +1.00 D or higher. Ishihara, CAD and CCT results were not detrimentally affected until +8.00 D. Yellow-blue discrimination was more affected by blur for the CAD than the CCT, which was not explained by the different colour spaces used or vectors tested.

Conclusion: False-positive findings on lantern colour vision tests with small apertures are likely to be increased in patients with blur due to uncorrected refractive error or ocular and visual pathway disease. Other colour vision tests with larger stimuli are more robust to blur.

KEYWORDS
CAD test, CCT, colour vision testing, Ishihara test, lantern tests, refractive blur, uncorrected refractive error

INTRODUCTION

The impact of refractive or neural blur on clinical and occupational colour vision test results, especially with newer lantern and computerised tests, is currently unclear. Refractive error results in light reflected from distant objects not being perfectly focussed onto the retina causing blur. Refractive error arises from genetic, environmental and medical factors and is remediated with spectacles, contact lenses or refractive surgery, thereby improving visual acuity (VA) and quality of life.[1] The prevalence of refractive error depends on geographic location, ethnicity and age, but uncorrected refractive error is the leading cause of moderate-to-severe vision impairment[2] with 157.5 million cases recorded globally in 2020.[3]

Red-green (R-G) colour vision deficiency (CVD) is a common congenital visual disorder affecting around 8% of male and 0.5% of female Caucasians[4,5] but is less prevalent in Asian, African and Native populations.[6] Diagnosis depends on severity (anomalous trichromacy and dichromacy) and on the photoreceptor type affected: protan defects affect L-cones while deutan defects affect M-cones.[7] Genetic R-G defects cause primary impairment in colour discrimination, with luminance discrimination strongly affected in protan

defects.[8] These defects can enhance contrast sensitivity[9,10] and VA for multigene dichromats[11] and anomalous trichromats.[9] Congenital CVD affecting the yellow-blue (Y-B) channel is rare (incidence ranges from 0.2% to 0.002%) and is equally distributed between sexes.[4] Lack of functionality of S-cones causes tritanopia.[7] The existence of genetic tritanomaly[5] remains unclear but tritanomalous colour confusions are common in normal ageing.[12,13]

Acquired CVD primarily depends on causative ocular and visual pathway disease (see Simunovic,[14] for a review) including progressive retinopathies,[15] optic neuropathies,[16] cortical damage[17] or toxicity.[18] Such disorders affect colour discrimination in both R-G and Y-B chromatic channels (more usually Y-B[8]) as well as significantly impair VA and/or visual fields.[6] Evidence from large surveys shows a 10.1% prevalence in a population 40 to 64 years of age[19] and a 20.8% prevalence in a population aged 58 to 102 years,[13] which is higher than that for congenital CVD.

Previous research (see Table 1) has assessed the effects of blur on performance for the Ishihara's tests for colour deficiency (Ishihara), American Optical Hardy, Rand and Rittler pseudo-isochromatic plates (HRR), Farnsworth–Munsell 100-Hue test (FM100), American Optical Corporation pseudo-isochromatic plates (AOC), Dvorine pseudo-isochromatic plates (Dvorine), Cambridge colour test (CCT) and Farnsworth–Munsell D15; however, results are not always in agreement. In a seminal study by Gordon and Field,[20] 15 colour vision normal (CVN) participants reported improved performance with Ishihara plates when image defocus was created with a projector (projection of plates leads to differences in hue, luminance and size compared with physical plates). The authors hypothesised that improved performance was due to the removal of high spatial frequencies with defocus, which acted as noise, increasing legibility of figures from their backgrounds. Taylor and Woodhouse[21] could not replicate this result with optical lens blur; performance on the Ishihara test for 10 CVN and 16 CVD observers was unaffected. However, blur that resulted in a decline in near VA to N8 did affect performance on the HRR test in CVD observers: deutans improved and protans worsened. When blur was increased (acuity degraded to N24), performance of both CVN and CVD groups returned to the unblurred baselines. Gordon[22] also replicated the improvement in Ishihara performance for an unspecified number of observers using optical blur that reduced near VA to N24.

Imposed optical blur also affects other colour vision test results. Brown et al.[23] found impairment in performance using part of the FM100 test with blurred vision (to J1, J6, J12 and J20; reported to be equivalent to ~N3.5, N8, N16 and N31) in 50 CVN observers. Long et al.[24] found impaired performance when testing with AOC and Dvorine plates with +2 to +4 D (dioptres) of imposed blur, but Ishihara performance was almost unaffected (it was also unaffected by differences in presentation time or viewing distance) for 90 CVN participants; a finding similar to that of Ng and Shih[25] who tested 25 CVN participants, but different from McCulley et al.[26] who tested 12 CVN participants and found the Ishihara test to be more sensitive to blur than the HRR test. A recent study[27] with 15 CVN participants indicated that FM100 and CCT results were significantly affected by +6 D blur, whereas the Ishihara was not, with all three tests being robust to +3 D of blur.

Key points

- Despite having normal colour vision and visual acuity, individuals may fail lantern tests, impacting diagnostic accuracy.
- Colour vision tests with stimuli of 1 degree or larger are relatively robust to blur, but test scores differ for high (8 D) blur levels.
- The impact of blur on colour discrimination thresholds with commercially available computerised tests depends on the red-green and blue-yellow colour axes tested and may vary with stimulus timing characteristics.

It is difficult to compare results across studies without examining specific details. For example, monocular versus binocular viewing leads to differences in VA of ~0.07 to 0.26 logMAR depending on the level of blur (e.g., 0.15–0.19 logMAR differences for blur levels of +2.00 and +2.50 D, respectively) due to binocular summation,[28] but more important than the levels of dioptric blur are the levels of VA during colour vision testing. Table 1 attempts to compare VA levels across studies by converting different near acuity units (N point and J values) to logMAR.[29,30] J values are non-standardised but were converted according to Table X-24 in Borish (p. 391).[30]

VAs from blur levels were estimated from data obtained from this and previous studies.[25,27,31] Viewing distances for colour vision tests also need to be accounted for, especially in uncorrected presbyopes who cannot accommodate to clear the target. However, most (although not all) studies have used blur to achieve a particular VA level, thereby bypassing any viewing distance issues.

Occupational practical tasks, notably marine hazards, led to the introduction of lantern tests that incorporate identification of coloured signal lights.[32] Use of lights can assess safety aspects of signal recognition in train drivers and aviation personnel,[33] although computerised tests presented on display monitors, such as the colour assessment and diagnosis test (CAD)[34] now serve a similar purpose. With lantern tests, it has previously been noted that an observer may fail the assessment without being colour deficient due to refractive blur[35] or a central scotoma.[36] Night myopia (an increase in myopic refractive error in dark conditions) can also cause normal observers to fail.[37] Computerised tests including the CAD and the CCT additionally allow measurement of discrimination thresholds in CVN and CVD participants.[34,38]

TABLE 1 Summary of studies where the effect of blur on colour vision results was investigated.

Reference	*N* (sample size)	Test	Testing conditions (distance, monocular/binocular if available)	Degradation levels	Result	Near acuity (N point)	Distance acuity (logMAR)	Blur (Dioptres [D])
Gordon & Field[20]	15 CVN	Ishihara	550 cm	Projected slides: focussed and defocussed	Focussed: 7 errors Defocussed: 2 errors Maximum legibility with defocus 220 cm in front of the screen	N/A	N/A	N/A
Taylor & Woodhouse[21]	10 CVN 16 CVD: 10 protans, 6 deutans	Ishihara	75 cm	N5 (participants' normal VA) Lens blur to N8 and N24 near acuities	CVN and CVD: Little difference in ease of recognition with and without blur	N5 N8 N24	≤0.2 0.4 0.9	0–1.00 1.75 4.00
		HRR			CVN: No errors CVD: N8: deutans: improvement in performance; protans: reduction N24: deutans and protans: performance returns to N5 levels			
Gordon[22]	Not reported	Ishihara	Binocular	Lens blur to N24 near acuity	The Ishihara dots run together so contours become continuous	N24	0.9	4.00
Brown, Govan & Block[23]	50 CVN	FM100 Hue (boxes 1 and 3)	40 cm	Lens blur to J1, J6, J12 and J20	Lowered levels of VA impair performance	N3.5 N8 N16 N31	≤0.0 0.3 0.7 1.0	0–0.50 1.50 3.00 4.75
Long, Lyman & Tuck[24]	90 CVN	AOC and Dvorine	76 cm Monocular	1.00 D 2.00 D 4.00 D lens @11 cm	Adversely affected by duration and increasing blur (2 to 4D)	N5 N10 N25	0.2 0.5 0.9	1.00 2.00 3.75
		Ishihara			Insensitive to changes in viewing duration and blur			
Thyagarajan et al.[27]	15 CVN	FM100 Hue	33 cm Monocular	1.00 D 3.00 D 6.00 D (after full ametropic correction for viewing distance)	Scores were affected >3 D blur	N2 N4	Median (IQ): −0.18 (nil)	0.00 1.00
		Ishihara	50 cm Monocular		No errors	N20 N40	0.1 (0.1–0.14) 0.84 (nil) 1.08 (1.08–1.1)	3.00 6.00
		Cambridge Colour Test	4 m Monocular		Effects seen >3 D blur.			
McCulley et al.[26]	12 CVN	D15	Near Monocular	Lens blur to 1.88–0.67 logMAR in 0.10 steps	Estimate of VA at which 5% of the population should experience a reduction in colour vision results: logMAR 1.40	N80	1.40	8.25
		Ishihara			logMAR 0.72	N16	0.72	2.75
		HRR			logMAR 1.10	N40	1.1	5.00

(Continues)

TABLE 1 (Continued)

Reference	*N* (sample size)	Test	Testing conditions (distance, monocular/binocular if available)	Degradation levels	Result	Near acuity (N point)	Distance acuity (logMAR)	Blur (Dioptres [D])
Ng & Shih[25]	25 CVN	Ishihara plates 1, 10 and 15	80 cm Monocular	Optical defocus tolerance levels (and VA) measured individually for at least 90% certainty identification	Plate 1 (Demo): 5.70 ± 1.52 D (1.13 ± 0.17 logMAR) Plate 10 (Vanishing): 3.68 ± 1.71 D (0.94 ± 0.28 logMAR) Plate 15 (Vanishing): 4.62 ± 1.56 D (1.06 ± 0.21 logMAR)	N25–N40	0.94–1.13 (at near)	3.68–5.70
		HRR plates 1, 7, 10 and 20			Plate 1 (Demo): 6.23 ± 1.61 D (1.20 ± 0.11 logMAR) Plate 7 (Vanishing): 1.23 ± 1.16 D (0.37 ± 0.31 logMAR) Plate 10 (Vanishing): 2.41 ± 1.31 D (0.63 ± 0.30 logMAR) Plate 20 (Diagnostic) 7.96 ± 2.03 D (1.34 ± 0.12 logMAR)	N8–N63	0.37–1.34 (at near)	1.23–7.96

Note: Visual acuity (VA) values in the shaded cells were obtained by converting the values given in the original publications to standard metrics.[29,30] Dioptric values in the shaded cells were obtained from blur versus monocular or binocular VA data based on Thyagarajan et al.,[27] Paudel et al.,[31] Ng and Shih[25] and the current study. When information on monocular versus binocular testing was not available, binocular data were used to estimate dioptric equivalents.

Abbreviations: AOC, American Optical Corporation pseudo-isochromatic plates; CVD, colour vision deficiency (any CVD type, e.g., anomalous trichromacy, dichromacy); CVN, normal colour vision; D15, Farnsworth–Munsell D15; Dvorine, Dvorine pseudo-isochromatic plates; FM100 Hue, Farnsworth–Munsell 100-hue test; HRR, American Optical Hardy, Rand and Rittler pseudo-isochromatic plates; Ishihara, Ishihara's tests for colour deficiency; J, Jaeger near VA system; N, point size VA system.

The aim of this study was to test whether CVN and CVD participants with normal VA pass two occupational colour vision screening tests, namely the Ishihara test[39] and the Fletcher–Evans clinical, aviation and marine lantern test (CAM),[40] a replacement for the Holmes–Wright lantern tests A (aviation) and B (marine). We also assessed the impact of imposed optical blur on CAM (aviation mode) and a computerised chromatic threshold test used for occupational testing, the CAD.[34] As impaired VA and/or neural blur are associated with acquired CVD,[14] the impact of blur was also assessed with the CCT,[38] an additional computerised chromatic threshold test.

METHODS

Pilot experiment: Do CVN and CVD adults with normal VA pass or fail current Ishihara and lantern screening tests?

Participants

All participants in both the pilot and main experiment were students from Anglia Ruskin University who gave informed consent before experimentation. Research protocols for both experiments were approved by the Anglia Ruskin University Research Ethics Committee to ensure that they complied with the principles of the Declaration of Helsinki. Twenty participants (10 males, 10 females) took part: 16 CVN, 4 (all males) CVD as classified with an anomaloscope. The average age was 22 ± 5.65 years. Participants had normal or corrected-to-normal VA of at least 0.18 logMAR (6/9) in the better eye, the stated requirement for the CAM lantern.[40] Applicants suffering from ocular and/or systemic pathology or who took medication with known ocular side effects were excluded. Participants wore habitual optical corrections for VA assessment and colour vision tests. Eight of the 16 CVN participants repeated the pilot experiment.

Procedure

VA (right eye, left eye and binocular) was measured with Early Treatment of Diabetic Retinopathy Study (ETDRS) logMAR letters presented using the Test Chart 2000[41–43] (Thomson Software Solutions, thomson-software-solutions.com/) under normal fluorescent room lighting. Colour vision was tested in the same order: binocularly with Ishihara pseudo-isochromatic plates[39] (38-plate edition) and the CAM lantern (Evans Instruments Ltd)[40] and then monocularly with the HMC (Heidelberg multi-colour) anomaloscope (TYP 47700, Oculus, oculus.de/en/) using the preferred eye.

A light cabinet (VeriVide, verivide.com/) ensured D65 illuminance for Ishihara testing. Each Ishihara plate was viewed at 75 cm with a viewing time of 4 s or less and participants were instructed to indicate the digit/s seen.

The number of errors and misreadings were recorded. Misreadings are answers not typical of CVD (e.g., on the first Ishihara plate, a CVN answer would be '8' and an R-G CVD answer would be '3', but an answer of '5' or '6' would be a misreading).

Lights in the CAM lantern were presented manually under ambient illumination of 80 lux (60-W desk lamp directed at the ceiling in a dark room). A mirror placed 3 m from both the spectacle plane of the participant and the face of the lantern next to the participant created a viewing distance of 6 m (as per manual diagram).[32] Care was taken to ensure that the lantern was aligned precisely with each participant's line of sight. With the CAM clinical mode, lights were white ($x = 0.4316$, $y = 0.4022$), red (light: $Y = 14.22$, $x = 0.6857$, $y = 0.3117$ and dark: $Y = 6.17$, $x = 0.7067$, $y = 0.2898$), green (bluish: $Y = 18.99$, $x = 0.2058$, $y = 0.3809$ and yellowish: $Y = 25.63$, $x = 0.2717$, $y = 0.5107$) and yellow ($Y = 6.02$, $x = 0.5813$, $y = 0.4144$).[40] After a demonstration with larger lights at 100% brightness (aperture D of 5 mm, subtense of 2.86 arcmin), participants named the colours of pairs of lights (aperture C of 3 mm; subtense of 1.72 arcmin): red, green, white or yellow. With the CAM aviation mode, lights are white, red (light and dark) and green (bluish and yellowish) with the colorimetric characteristics being the same as in clinical mode, and participants named red, green or white. A demonstration used Aperture A at 100% brightness and a diameter of 1.6 mm, subtense of 0.92 arcmin; for testing, the same aperture at brightness of 10% was used. Lights were presented for 2 s and the response time limit was 5 s. Errors were counted when misnaming any colour. Misnaming red or green for any other colour was an instant failure while other misnaming errors allowed for two further attempts. Any misnaming error on additional runs was deemed a failure.

The HMC anomaloscope was conducted manually in a dimly lit room. The examiner adjusted the red/green mixture knob under the participant's guidance to match the two halves of the circular visual field; the participant adjusted the luminance knob of the yellow comparison light to achieve a match. If a match between the two halves was achieved, participants pressed one button; if this could not be achieved, they pressed the other button.

Experiment: Effect of imposed lens blur on colour vision test results for CVN adults

Participants

There were 15 CVN participants (6 males, 9 females) with an age range of 19–30 years (average age 22.3 ± 2.7 years). Six of the 15 participants repeated all tests. Sample size was based on power calculations for similar psychophysical studies conducted in our laboratory and is in line with several other investigations (see[20,26,27] in Table 1). For example, when testing VA, to find an effect size of 0.10 logMAR as a significant difference in VA,[44] with a measurement error standard deviation of ±0.10 logMAR,[45–47] a significance level $p = 0.05$ and power of 0.80, a sample size of $N = 16$ was estimated as being required to find a statistical difference, should one exist.

Procedure

Table 2 provides details of viewing distances, optical lens combinations (viewing distance and blurring) and stimulus details for colour vision tests: Ishihara test, CAM lantern test (aviation mode), CAD (2.0, City Occupational Ltd, researchcentres.city.ac.uk/applied-vision/avot) and CCT (2.30, Cambridge Research Systems, crsltd.com). The order of colour vision testing was randomised for each participant. Testing was conducted binocularly firstly without blur and then with different levels of imposed blur. There is minimal chance that participants could remember sequences of

TABLE 2 The viewing distance, stimulus size and optical blurring lenses (after accounting for viewing distance) used.

Test	Viewing distance	Stimulus size (° or ′)	Viewing distance lens (D)	Estimated imposed blur (D)
ETDRS logMAR Acuity	6 m	Letter size varies, e.g., 0.00logMAR = 5′ letter size	0.00	+0.50, +1.00, +2.00, +4.00, +6.00, +8.00
Ishihara pseudo-isochromatic plates (38-plate edition)	0.75 m	Figure size[a] (1.0–1.4°)[a] Stroke width[a] (0.3–0.6°)[a] Noise diameter (3–21′)[a] Smallest 2 noise diameter: 4–6′[22]	+1.25	+4.00, +6.00, +8.00
Fletcher–Evans CAM Lantern Test (Aviation mode)	6 m (via mirror)	Aperture A10 size: 0.92′[32] Separation: 11.46′[32]	0.00	+0.50, +1.00, +2.00
Colour Assessment and Diagnosis Test (CAD)	1.4 m	Square side: 1.6°[51] 5 checks/side: Noise side size: 19′	+0.75	+2.00, +4.00, +8.00
Cambridge Colour Test (CCT)	3 m	C outer diameter: 4.3°[38] C gap: 1.00°[38] Noise diameter range: 2.8–5.7′[53]	+0.25	+2.00, +4.00, +8.00

Abbreviations: CAM, Clinical, avaiation and marine lantern; ETDRS, Early Treatment of Diabetic Retinopathy Study.

[a]Indicates manually measured.

Ishihara numbers or CAM paired-light presentations after having seen them first without blur, and in addition, fatigue would balance out any learning effects. CAD and CCT stimulus presentations were always randomised. To calculate the imposed blur, the viewing distance was accounted for. For example, a +2 D lens does not blur a stimulus at a 50 cm viewing distance, and to obtain +2 D of imposed blur at 50 cm, a +4 D lens is required. Thus, a lens to create imposed blur was placed in a trial frame and aligned optimally. Different blur levels were chosen for each test based on pilot data obtained prior to this study and from results in the literature.

The CCT was conducted in a dark room at a viewing distance of 3 m. The stimulus, a large letter C was presented onto a calibrated CRT screen and the participant indicated the direction of the gap in the C (up, down, right or left) using a response box. The optotype was presented for 4 s and responses were accepted until 3 s after offset. The CCT trivector test measures chromatic detection thresholds along three vectors in CIE 1976 (u', v') space from a reference achromatic point ($u'=0.254$, $v'=0.499$).[38] Reference scores for CVN observers based on the test instructions[48] are ≤100 for protan and deutan axes and ≤150 along the tritan axis. Higher scores are indicative of CVD, and dichromats typically score >750 along one axis.[48]

The CAD was also conducted in a dark room at a viewing distance of 1.4 m. Participants indicated towards which corner of the screen the stimulus box moved (up and right, up and left, down and right or down and left) using a response box. Stimuli were presented for 600 ms[49] with no response time limit. The CAD test measures chromatic detection thresholds along 16 directions in CIE 1931 (x, y) chromaticity space from a reference white point ($x=0.305$, $y=0.323$),[34] allowing estimates of R-G and Y-B thresholds.[50] Although the CAD programme measures threshold discrimination ellipses, thresholds from vectors near protan and deutan axes were averaged, as were thresholds from vectors near the blue-yellow axis.[51] CAD units of measurement (standard normal units, SNU) are based on mean colour thresholds for 330 healthy, young, normal trichromats, with the R-G limit (most common genetic deficiency) being ~≥1.75 to 2 depending upon age.[52] The suggested failure criteria for air traffic controllers for threshold measures are as follows: R-G SNU > 1.77 and normal Y-B > 1.75 SNU.[51]

Data analysis

Statistical analyses were performed using IBM SPSS version 28 (ibm.com) and StatSoft Statistica 8.0 (statistica.com). Data were analysed using repeated measures analysis of variance (ANOVA) with Greenhouse–Geisser corrections for any violations of sphericity.

RESULTS

Pilot experiment: Do CVN and CVD adults with normal VA pass current Ishihara and lantern screening tests?

One-way ANOVAs comparing first and repeated measurements of VA, the number of errors made with the CAM lantern (clinical) and anomaloscope matching ranges and midpoints were conducted for eight CVN observers. No significant differences were found between these measures (Table 3). Ishihara errors (and misreadings) and CAM

TABLE 3 Mean measures of repeatability for eight colour vision normal participants.

Test	Run 1 (CI)	Run 2 (CI)	*p*-Value
logMAR acuity for the best eye	−0.10 (−0.21 to 0.02)	−0.13 (−0.24 to 0.02)	0.19
logMAR acuity for the wore eye	−0.07 (−0.16 to 0.02)	−0.08 (−0.18 to 0.02)	0.35
Ishihara (errors)	0.00 (0.00 to 0.00)	0.25 (−0.34 to 0.84)	—
Ishihara (misreadings)	0.50 (0.05 to 0.95)	1.00 (1.00 to 1.00)	—
CAM lantern clinical (errors)	0.50 (0.05 to 0.95)	0.13 (−0.17 to 0.42)	0.08
CAM lantern aviation (errors)	0.13 (0.17 to 0.42)	0.00 (0.00 to 0.00)	—
Anomaloscope (matching range)	6.31 (4.60 to 8.0)	7.89 (4.97 to 10.8)	0.21
Anomaloscope (midpoint)	39.89 (38.75 to 41.04)	40.54 (39.37 to 41.72)	0.33

Abbreviation: CAM, Clinical, avaiation and marine lantern; CI, confidence interval.

TABLE 4 Performance metrics of Ishihara and CAM lantern test (clinical mode CAM-C; aviation mode CAM-A) in comparison with the diagnosis obtained with the Heidelberg multi-colour anomaloscope.

Test	TP	FP	TN	FN	Sensitivity (CI)	Specificity (CI)	PPV	NPV
Ishihara	4	0	16	0	100.00 (–)	100.00 (–)	100.00	100.00
CAM-C	4	4	12	0	100.00 (–)	75.00 (56.02%–93.98%)	50.00	100.00
CAM-A	4	3	13	0	100.00 (–)	81.25 (64.14%–98.36%)	57.14	100.00

Abbreviations: CAM, Clinical, avaiation and marine lantern; CI, Wilson's score confidence interval; FN, false negative; FP, false positive; NPV, negative predictive value; PPV, positive predictive value; TN, true negative; TP, true positive.

lantern (aviation) errors could not be analysed with this method because the data lacked variance. Therefore, only first measures were considered, which more closely mimics what happens in clinical practice. Contingency tables were constructed for Ishihara and CAM lantern tests and compared against anomaloscope results—see Table 4.

Sensitivity (the rate at which a diagnostic test identifies true positives) and specificity (the rate at which a diagnostic test identifies true negatives) for the Ishihara results were both 100%. However, for the CAM lantern test (clinical mode), sensitivity and specificity were 100% and 75%, respectively, whereas for the CAM lantern (aviation mode), the respective values were 100% and 81.25%. The CAM lantern test showed perfect negative predictive value (NPV) scores but imperfect positive predictive value (PPV) scores for both clinical and aviation modes as a consequence of false-positive results. For both modes, the most common error made by CVN participants was misnaming white as green. Four of 16 CVN participants 'failed' the clinical mode of the CAM lantern and 3 of 16 'failed' the aviation mode, despite the small range of VA (−0.30 to 0.00 logMAR; 6/3 to 6/6). Figure 1 shows the percentages of errors (total errors/total possible ×100%) made for CVN participants with −0.30 logMAR (6/3) to 0.00 logMAR (6/6) VA after one test session. In the aviation mode, average error rate was greater for those with 0.00 logMAR than with −0.30 logMAR VA. For this small sample size and range of VA, the level of acuity did not correlate significantly with the matching ranges of the anomaloscope, the number of errors made on the Ishihara test or the number of errors with the CAM (clinical) or CAM (aviation) modes ($r = 0.18$, −0.23, −0.009 and 0.30, respectively; $p = 0.50$, 0.39, 0.97 and 0.27). More CVN participants who failed the CAM (clinical) or CAM (aviation) modes were spectacle wearers (66.7% and 75%,

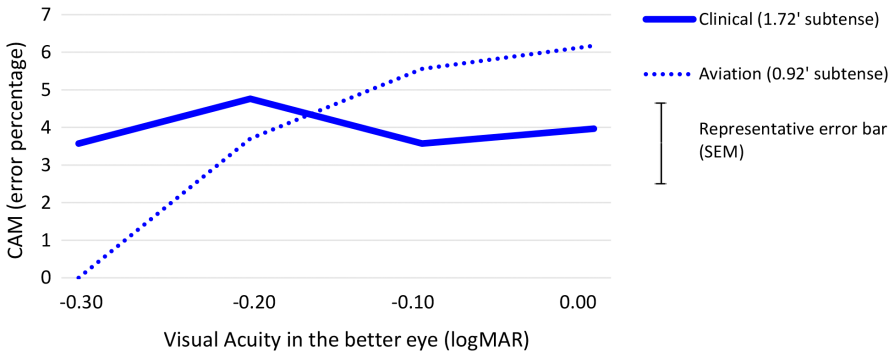


FIGURE 1 Error percentage on the first trial for CAM lantern clinical mode (solid thick line) and aviation mode (dotted line) for −0.30, −0.20, −0.10 and 0.00 logMAR visual acuities. The representative error bar (SEM average) is the actual size based on the *Y*-scale of the graph. CAM, Clinical, avaiation and marine lantern.

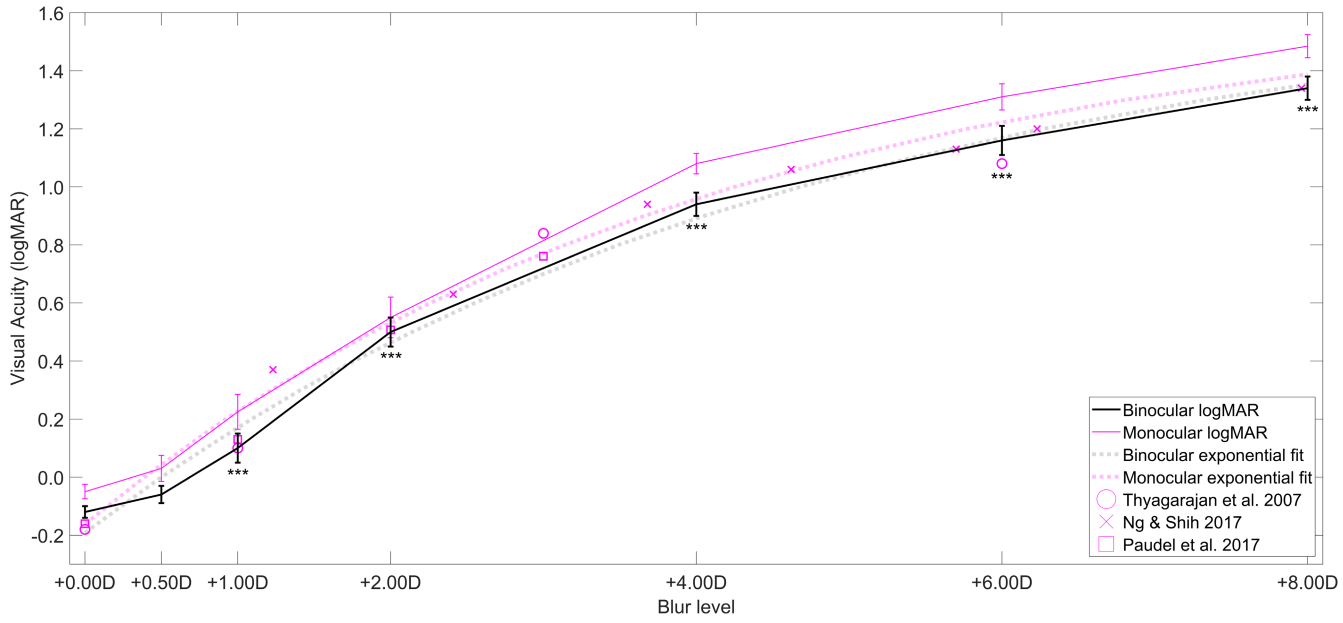


FIGURE 2 Monocular visual acuity (VA) (mean of the right and left eyes) from the current study as well as from previous studies by Thyagarajan et al.,[27] Paudel et al.[31] and Ng & Shih,[25] as binocular VA from the current study as a function of blur. Error bars indicate ±1 standard error of the mean. The dotted curves are the best-fitting exponential functions to the data. Model fits were used to estimate equivalent logMAR VAs in Table 1 from dioptric blur studies.

respectively) compared with those who passed (53.8% and 50%, respectively). However, VAs were not statistically different between spectacle and non-spectacle wearers.

Main experiment: Effects of imposed lens blur on VA and colour vision test results for CVN adults

Test repeatability

Two statistical analyses were used to assess the repeatability of the test results ($N = 6$). Two-way, within-subject ANOVAs with repeated measures (first, second) and blur levels (see Table 2) were conducted for logMAR, Ishihara and CAM lantern scores. Three-way ANOVAs were conducted on the CCT and CAD discrimination thresholds with repeated measures, blur level and colour axis (Protan, deutan and tritan for CCT; R-G and Y-B for CAD) as within-subject factors. No significant difference was found between the scores obtained from two measures for the logMAR, Ishihara and CAM lantern tests. For the CCT and CAD tests, the effect of repeated testing depended on the blur level (CCT: $F(3, 15) = 7.27$, $p = 0.004$; CAD: $F(3, 15) = 5.12$, $p = 0.01$) with a significant improvement on repeated testing being observed with +8.00 D of induced blur (post-hoc Tukey; CCT: $p = 0.007$; CAD $p = 0.001$). The main analysis now considered only the first test measure ($N = 15$).

Effects of imposed lens blur

Binocular VA data shown in Figure 2 (black solid line) were analysed with a one-way ANOVA with blur (0.00, +0.50, +1.00, +2.00, +4.00, +6.00 and +8.00 D) as the repeated factor. As expected, blur had a significant impact on logMAR VA ($F(6, 84) = 328.19$, $p < 0.001$; see Figure 2). In comparison to the no-blur condition, VA was significantly reduced with +1.00 D or more blur (i.e., +2.00, +4.00, +6.00 and +8.00 D, all $p < 0.001$). With the statistical power available for the sample size ($N = 15$), this provides a useful metric for interpreting the impact of blur on the colour vision test results.

The effects of imposed blur on colour vision tests are shown in Figures 3 and 4. For the Ishihara and CAM lantern tests (Figure 3), raw error scores were converted to percentage errors (total errors/total possible ×100%) to enable comparison. A one-way ANOVA conducted on the Ishihara error percentage scores (including misreadings) found a significant effect of blur ($F(3, 42) = 6.43$, $p = 0.001$; see Figure 3a). Tukey post-hoc comparisons only showed a significant effect between 0.00 D and the highest blur level (+8.00 D, $p = 0.04$).

A one-way ANOVA conducted on the error percentage scores for the CAM lantern (Aviation) test showed a significant effect of blur ($F(3, 42) = 30.81$, $p < 0.001$, see Figure 3b). Tukey post-hoc comparisons showed differences between 0.00 and +1.00 D, as well as 0.00 and +2.00 D (both $p < 0.001$).

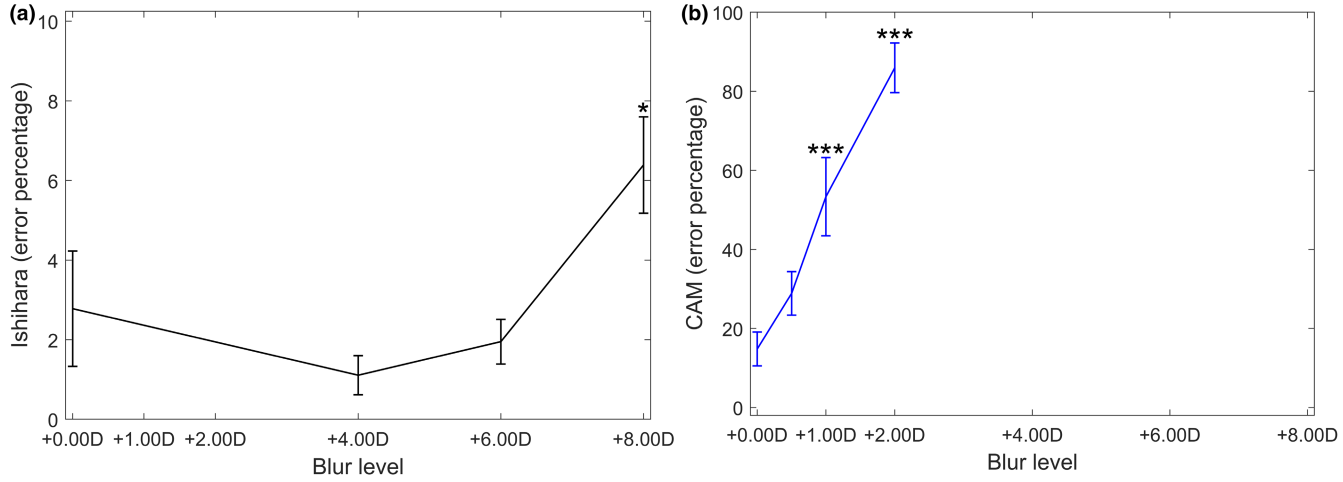
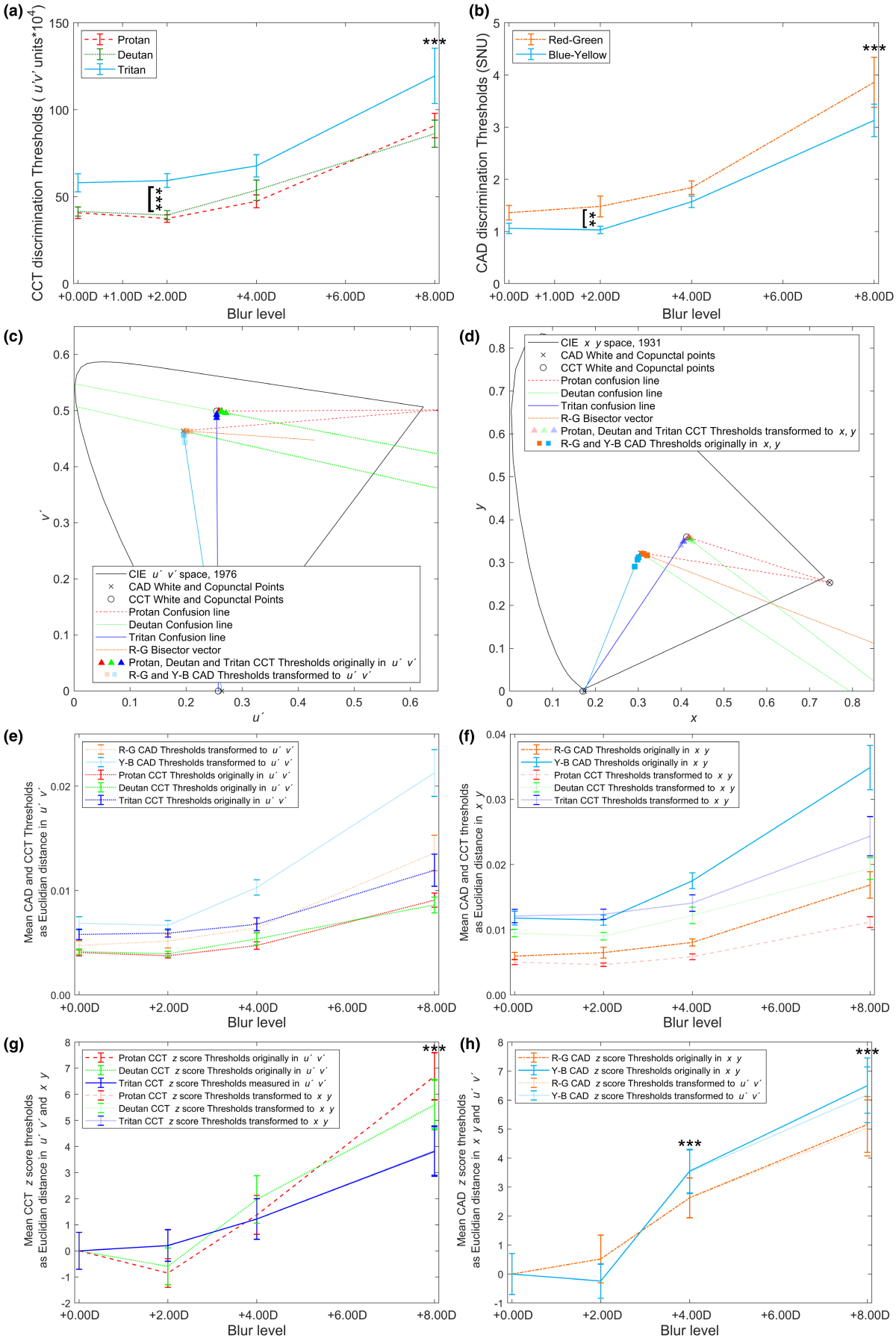


FIGURE 3 Effects of imposed optical blur on the mean error percentage scores for the Ishihara (a) and Fletcher–Evans CAM lantern (b) tests. Error bars indicate ±1 standard error of the mean. *Significantly different from the no-blur condition at $p < 0.05$; ***significantly different at $p < 0.001$. CAM< clinical, aviation and marine lantern.

FIGURE 4 Effects of imposed optical blur on Cambridge colour test (CCT) and colour assessment and diagnosis (CAD) test discrimination results. (a) CCT raw thresholds ($u'v'$ units) $\times 10^4$, (b) CAD raw thresholds (standard normal units, SNU). (c) CCT (triangles) and transformed CAD (squares) thresholds plotted along the colour axes in CIE (1976) u', v' space. (d) CAD and transformed CCT thresholds plotted along colour axes in CIE (1931) x, y space. (e) CCT and transformed CAD discrimination thresholds as Euclidean distances in CIE (1976) u', v' space versus blur. (f) CAD and transformed CCT discrimination thresholds as Euclidean distances in CIE (1931) x, y space versus blur. (g) CCT raw and CIE (1931) x, y space z-scores. Note that some coloured lines are difficult to see as they are extremely close to others. (h) CAD raw and CIE (1976) u', v' space z-scores versus blur. Raw thresholds are plotted as solid symbols or lines. Transformed thresholds are plotted as transparent symbols or lines. CCT: red dashed, green dotted and blue solid lines for protan, deutan and tritan axes respectively. CAD: orange dashed-dotted and light blue solid lines are for red-green (R-G) and blue-yellow (B–Y) axes. *Significantly different from the no-blur condition at $p < 0.05$; **significantly different at $p < 0.01$; and ***significantly different at $p < 0.001$. Error bars indicate ±1 standard error of the mean.



Discrimination thresholds obtained from the CCT measured in the CIE 1976 (u', v') chromaticity space, and for the CAD test measured in CIE 1931 (x, y) space as SNUs, are shown in Figures 4a,b respectively. A two-way repeated measures ANOVA with colour axis (protan, deutan and tritan) and blur (0.00, +2.00, +4.00 and +8.00 D) as factors conducted on CCT discrimination thresholds showed a significant main effect of blur ($F(1.41, 19.80) = 40.55$, $p < 0.001$, see Figure 4a) with post-hoc tests showing a significant difference between 0.00 and +8.00 D ($p < 0.001$). A significant effect of axis ($F(2, 28) = 13.83$, $p < 0.001$) was also found, with discrimination along the tritan axis being significantly worse than along the protan and deutan axes (both $p < 0.001$).

Statistical analysis on the CAD reported that discrimination thresholds also showed a significant main effect of blur ($F1.16, 16.25) = 38.85$, $p < 0.001$, see Figure 4b) with a significant difference again being seen between 0.00 and +8.00 D ($p < 0.001$). A significant main effect of axis ($F(1, 14) = 12.99$, $p < 0.01$) was also observed, with discrimination along the Y-B axis being significantly better than the R-G axis ($p < 0.01$).

To investigate how discrimination thresholds may have been affected by the use of different chromaticity spaces, thresholds from CCT were converted to CIE 1931 (x, y) space, while those from CAD were converted to CIE 1976 (u', v') space (Figures 4c,d). To convert thresholds from CCT reported values (thresholds $\times 10^4$),[53] confusion lines that converged to co-punctal points as reported by Regan et al.[38] and standard equations[54] were used. For the CAD test, discrimination thresholds reported in SNU were first converted to distances in CIE 1931 (x, y) space using values of 4.37×10^{-3} for R-G and 11.15×10^{-3} for Y-B.[55] Although the CAD test measures discrimination thresholds in 16 directions, an assumption was made that when averaged to provide values for R-G and Y-B vectors, these fell along confusion lines that converged to the co-punctal points reported by Smith and Pokorny.[56] In the present study, as in the design of any colour vision test, it was not possible to determine the exact angle of confusion axes for individual participants as that would require the measurement of factors[57] such as the crystalline lens, macular pigment, optical density, photoreceptor distributions and L:M ratios in individual participants. Discrimination thresholds in common chromaticity spaces are shown in Figure 4c (CIE 1976 u', v') and 4d (CIE 1931 x, y). The effects of imposed blur on discrimination thresholds followed similar patterns in both spaces, particularly the Y-B differences found between tests (see Figures 4e,f).

To allow direct comparison between raw (and transformed) discrimination thresholds obtained from the CCT and CAD tests, z-scores for each test (Figures 4g,h) were calculated using the following formula:

$$z\text{-score} = \left[\text{blur result} - \text{mean no blur result}\right] / \sqrt{\frac{sd_1^2}{n_1} + \frac{sd_2^2}{n_2}} \quad (1)$$

where the *blur result* represents the CCT/CAD scores at a particular blur level, the *no blur result* indicates CCT/CAD scores at +0.00 D averaged across the group, sd_1^2 represents the group standard deviation at +0.00 D and sd_2^2 indicates the group standard deviation at each blur level. The number of participants, n_1 and $n_2 = 15$ for both the no-blur and blurred conditions.

Z-scores based on data in both colour spaces were very similar (see Figures 4g,h), so statistical analysis was conducted on z-scores based on the raw discrimination thresholds from the original colour spaces for each test. A two-way repeated measures ANOVA with colour axis (protan, deutan and tritan) and blur (0.00, +2.00, +4.00 and +8.00 D) as factors was conducted on the CCT z-scores (Figure 4g). There was a significant effect of blur ($F(3, 42) = 33.89$, $p < 0.001$) and a near-significant interaction between axis and blur ($F(6, 84) = 2.19$, $p = 0.05$). Tukey post-hoc comparisons showed the effect of +8.00 D blur was significantly different from the no-blur condition ($p < 0.001$). A similar two-way ANOVA with colour axis (R-G and Y-B) and blur as factors was conducted on the CAD z-scores (see Figure 4h). There was a significant effect of blur ($F(3, 42) = 32.76$, $p < 0.001$), which depended on the colour axis ($F(3, 42) = 4.51$, $p = 0.008$). Tukey post-hoc comparisons revealed that the 0.00 D condition was different from both +4.00 and +8.00 D of blur along both R-G and Y-B axes (all $p < 0.001$). This significant interaction must arise from a cross-over effect between colour axes at low versus high levels of blur. At higher levels of blur (+4.00 and +8.00 D), discrimination expressed as z-scores was less affected by blur along the R-G axis.

As CAD and CCT assess discrimination thresholds for specific chromatic channels, we attempted to compare the effects of blur on both tests within one analysis (Figures 4g,h). A three-way repeated measures ANOVA with test (CCT and CAD), axis (protan for CCT vs. R-G for CAD; tritan for CCT, Y-B for CAD) and blur as factors was conducted on the z-scores. This analysis confirmed a significant overall effect of blur ($F(1.40, 19.53) = 42.90$, $p < 0.001$), which depended on the colour axis and blur level ($F(3, 42) = 6.50$, $p = 0.001$). Tukey post-hoc comparisons showed that discrimination along the tritan CCT axis was less affected by blur than the Y-B CAD axis at the +8.00 D blur level (CCT 3.68 ± 0.95 vs. CAD 6.28 ± 0.95, $p = 0.03$). The same analysis conducted using the deutan (rather than the protan) colour axis data for CCT revealed the same result: a significant effect of blur ($F(1.33, 18.65) = 43.04$, $p < 0.001$), which depended on colour axis and blur level ($F(3, 42) = 4.73$, $p = 0.006$). A significant difference was found such that the tritan CCT axis was less affected by +8.00 D of blur, compared with the Y-B CAD axis ($p = 0.02$).

DISCUSSION

The results of the pilot experiment showed that CVN participants with normal VA (−0.30 to 0.00 logMAR) were classified as CVN on the Ishihara test, but a significant

number of them failed the CAM lantern tests (all four CVD participants failed both tests). Therefore, minimal amounts of neural or refractive blur can affect occupational test results for CVN participants, and assessing the impact of optical blur on test results, such as from uncorrected refractive error, is important (see Figure 1, aviation mode of the CAM lantern test). Minimal levels of blur are likely to have contributed to previous reports of CVN participants failing lantern tests: up to 8% failed the Board of Trade lantern[58] and Holmes–Wright lantern (type B),[59] whereas ~13% with VA of logMAR 0.18 (6/9) or better made errors on the first run of the CAM lantern.[32] Imposed optical blur (+0.50 to +2.00 D) effects on the CAM lantern (aviation) results were statistically similar to those for VA, that is, degraded significantly by +1.00 D of blur. Similar outcomes for VA and CAM (aviation) results are likely due to the effects of blur on stimulus resolution. For example, the letter stroke width for a logMAR 0.00 (6/6) letter size is 1′ and the diameter of the aviation test aperture is 0.92′. For the CAM lantern test though, factors other than resolution, such as specific chromaticities of target lights, may also have influenced blur results. These results demonstrating the impact of different levels of blur on the CAM lantern test (aviation mode) outcomes agree with those found previously for identification of coloured lights such as those in lantern tests (see Figure 2 in Wood[60]). In their study ($N = 15$ young adults; $N = 15$ older adults), detrimental effects were found from +0.50 D of blur on red lights, while +1.25 affected yellow signals. Patients with acquired CVD often also have degraded VA, so assessing the impact of blur on colour vision tests (e.g., CAD and CCT) designed to monitor acquired CVDs is also important.

The Ishihara, CCT and CAD tests were more robust to higher levels of blur than the CAM lantern. For the Ishihara, the first level of blur used (+4.00 D) showed a trend towards better performance than the no-blur condition, although this difference was not statistically significant. The improvement in performance may be similar to that reported by Gordon[20,22] who found Ishihara plates to be more legible when seen as defocused images. As they proposed, it is likely that filtering out higher spatial frequencies with blur can increase the legibility of the figure from the background in the Ishihara plates (although this result must be interpreted with caution as projection of plates leads to differences in hue, luminance and sizes when compared with the physical plates). This possible slight improvement should be considered when testing for CVD in participants with uncorrected refractive error, or neural blur such as in amblyopia, with VAs in the range of ~0.80 to 1.10 logMAR. However, this effect is unlikely to result in a CVD patient passing the test due to the large number of errors typically made (97.51% of individuals with CVD made six or more errors on 16 of the 24 plates in an Ishihara test).[61]

Differences in the effects of blur on discrimination thresholds along different colour axes were investigated by transforming the data from CCT and CAD tests to each other's chromaticity space and by statistically analysing z-scores for CCT (protan, deutan and tritan) and CAD (R-G and Y-B) axes. When the CCT and CAD z-scores were compared, discrimination along the Y-B axis for CAD was worse than along the tritan axis for the CCT, particularly as blur levels increased (reaching statistical difference at +8.00 D). Both these results and those of others[62] show that discrimination thresholds can depend on practice, but this was only true for the highest level of blur in both tests. The difference was also not likely to be related to the stimulus size (the size of the gap in the letter C for the CCT was 1° vs. a square side size of 1.6° in the CAD, see Table 2). Rather, it may be due to differences in temporal/motion characteristics incorporated into the CAD test (CCT has a static stimulus with noise, whereas the CAD stimulus square is in motion within dynamic noise) or differences in test stimulus duration (CCT 4 s; CAD 0.6 s). There were no significant differences in response to blur between the CCT and CAD for R-G (or protan/deutan) discrimination, so that blur appears to affect Y-B channels that process motion or temporal information selectively. Previous research has shown that when the same-size stimuli are temporally modulated (1 Hz),[63] Y-B discrimination is worse than R-G discrimination or static Y-B discrimination, with this difference being present at the fovea, in the periphery and across a wide range of stimulus sizes (widths of 0.125–16°).[63] On the other hand, in the static case (CCT), Y-B discrimination for high levels of imposed blur was affected less than for R-G discrimination. Chromatic aberration is higher for Y-B than R-G stimuli,[63] and sensitivity to high-[63] and mid-range spatial frequencies[64] is lower for static Y-B than R-G stimuli so that optical blur might be expected to have less impact on static Y-B discrimination thresholds. The Y-B channel might be more susceptible or vulnerable to disease (see Simunovic, for a review)[14] and so it also may be more susceptible to blur than the R-G channel. The present results suggest that both hypotheses, that is, that B-Y stimuli might be more susceptible or less susceptible to blur, could be correct, depending on the temporal characteristics of the stimulus. An alternative possibility is that Y-B discrimination thresholds differ in the CAD versus the CCT due to different vectors being tested in chromaticity space, leading to different discrimination ellipses. However, MacAdam ellipses (in CIE 1931 x, y space)[65] along the transformed CCT Y-B vector are longer than those near the CAD Y-B vector (see Figure 4d), and so if this were true, discrimination thresholds should be worse for the CCT than the CAD test, which is the opposite of what was measured.

As visual disorders and ocular disease affect Y-B more than R-G channels,[8] and are often associated with degraded VA, these findings deserve further investigation to determine which paradigm is most sensitive to changes in perception with disease progression. When testing computerised thresholds, it is important to ensure any refractive error is fully corrected, as significant uncorrected ametropia could lead to loss of colour discrimination in addition to

the decrements that occur with disease, in particular with the CAD measured along the Y-B discrimination axis. These results show that for this discrimination threshold to be impaired (defined as >mean + 2SD), VA would have to be degraded to ~1.34 logMAR.

The results for the static CCT test (Figure 4g) suggest that discrimination along the tritan axis was less affected by high levels of blur than along the protan/deutan axes, but may be more affected at low levels of blur (the effects of blur on CCT colour axis: $p = 0.05$). This finding may help to explain an apparent discrepancy in the literature as to how blur impacts results with the Ishihara test versus the HRR plates.[21,25,26] For low levels of blur, such as those used by Ng and Shih[25] who tested 25 CVN subjects (mean age = 26.6 ± 2.9 years), HRR test results were found to be more affected by blur than the Ishihara test. With the HRR test, performance on the vanishing plates was degraded to a criterion level with monocular VAs of ~0.37 to 0.63 logMAR using 1.20 to 2.40 D blur, equivalent to approximately +1.75 to 2.75 D of blur in the current study. With the Ishihara test, monocular acuities of ~0.94 to 1.06 logMAR were required to achieve the same criterion level. Sensitivity to blur depended on the plate type (i.e., classification plates required more blur than vanishing plates). For high levels of blur, such as those used by McCully et al.[26] who tested 12 CVN observers (age range 20–61 years), the Ishihara test was found to be more sensitive to blur (for VAs ≥0.67 logMAR) than the HRR test, with the difference being significant for VA ≥0.97 logMAR, which is roughly equivalent to ≥+5 D for participants in the current study. The Ishihara only tests for R-G defects, whereas the HRR tests for both R-G and Y-B defects. It is possible (see Figure 4g) that the HRR results were more affected by low levels (+2 D) of blur,[25] whereas the Ishihara test was more affected by higher levels of blur (i.e., +4 to +8 D).[26] The effects of blur will depend on the spatial characteristics and colour contrast of the test plates.[25] In the current study, the results were averaged across all plate types for the Ishihara test.

Overall, the results of this study provide important insights into the effects of blur on tests commonly used to assess colour vision for occupational and clinical diagnostic purposes. A larger sample size would have increased the statistical power such that the effects of lower dioptric levels of blur were more likely to have reached significance, while the observed interactions reported here may have been more statistically robust. These findings have practical implications for the administration and design of such tests, particularly in situations where blur or degraded VA may be present as in patients with uncorrected refractive error, ocular disease that reduces VA, or both.

AUTHOR CONTRIBUTIONS

Leticia Álvaro: Conceptualization (supporting); data curation (equal); formal analysis (lead); methodology (supporting); software (equal); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Monika A. Formankiewicz:** Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); software (equal); supervision (equal); writing – review and editing (equal). **Sarah J. Waugh:** Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (lead); investigation (equal); methodology (equal); project administration (equal); resources (equal); software (equal); supervision (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

All authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

PATIENT CONSENT STATEMENT

All participants gave informed consent before experimentation.

ORCID

Leticia Álvaro https://orcid.org/0000-0003-2065-7491
Monika A. Formankiewicz https://orcid.org/0000-0002-9271-3782
Sarah J. Waugh https://orcid.org/0000-0002-8899-4702

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