Cone Contrast Test for Color Vision Deficiency Screening Among a Cohort of Military Aircrew Applicants

Isaac W. Chay; Shawn W. Y. Lim; Benjamin B. C. Tan

PURPOSE: To evaluate the use of the Cone Contrast Test (CCT) as a color vision screening tool in an Asian population of aircrew applicants and compare it against the Ishihara Psuedo Isochromatic Plates (PIP) – Edridge Lantern Test (ELT) screening pathway, assessing its impact on attrition with CCT cut-off scores of 55 and 75.

METHODS: This is a retrospective review of 862 Republic of Singapore Airforce aircrew applicants tested with CCT and Ishihara PIP–ELT combination as screening. CCT repeatability was analyzed by comparing the subject's interocular (right vs. left eye) scores measured as the coefficient of repeatability (COR), with COR differing by ≥15 points considered to be outside normal limits.

RESULTS: Of the applicants, 17 (1.97%) failed to achieve a CCT score of ≥55 (5 protan, 12 deutan), while 26 (3.02%) applicants failed to achieve a score ≥75 (5 protan, 21 deutan). Of the 17 applicants who obtained a CCT score of <55, 16 failed the Ishihara PIP test. The only applicant who passed the Ishihara PIP test had a CCT score of 50. Of all applicants, 1.7% had a COR of ≥15, with 93.3% of them identified as color vision deficient (CVD). Our results demonstrated excellent test repeatability, with 99.9% (835 out of 836) of color vision normal (CVN) applicants achieving a COR of <15 points.

CONCLUSION: Our study demonstrated a high correlation between the CCT (passing score of ≥55) and the Ishihara PIP. Employing the CCT with a passing score of ≥75, instead of the Ishihara PIP–ELT combination, led to an increase in attrition rate of 0.7–3.0%.

KEYWORDS: Cone Contrast Test, Republic of Singapore Air Force, color vision screening, retrospective review, Ishihara Psuedo Isochromatic Plates, Edridge Lantern Test.

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Color vision testing was first introduced by the Royal Flying Corps during the First World War because of the importance of identifying the color and markings of enemy aircraft, recognizing colored flares and light signals, and assessing terrain to pick out landing places in an emergency.[19] Over the years, the importance of color vision in aviation has evolved from tasks involving the perception of the external environment to also include the interpretation of colors within the cockpit. With the increasing use of color-coded information in aviation signals and multifunctional monitors and displays in newer generation aircrafts, the visual requirements for color vision in modern military aviation is more important than ever. Color vision deficiency (CVD) in a military pilot or aircrew may lead to a disadvantage in the efficient perception of colors in multicolored displays, terrain maps, navigation lights, and the modern man-machine interface in the cockpit.[13] Increasing severity of CVD has also been shown to be associated with decreasing operational performance, measured as speed and accuracy in performing a color-related task;[10] hence, the impact of CVD on the performance of an aircrew for time-critical tasks and the overall safety in military aviation operations cannot be underestimated.

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The color vision of a military aviator can be divided into two broad categories: those who have normal color vision (CVN) and those with CVD sufficiently mild to ensure safe performance in the aviation environment, termed color-safe.[5] Conventional color vision tests include pseudoisochromatic plates (e.g., Ishihara, Dvorine), arrangement tests (e.g., Farnsworth D15, Farnsworth-Munsell 100-Hue), lantern tests (Farnsworth, Edridge-Green), and the anomaloscope. The development of computerized color vision tests first began in the 1980s, but their use was mainly limited to research purposes due to their associated high costs.[8] With the advancements in technology and increased availability in the form of commercial off-the-shelf products, there has been an emergence of several computerized tests in the screening and assessment of color vision.

For many years, the Republic of Singapore Air Force (RSAF) has used the Ishihara Psuedo Isochromatic Plates (PIP) and the Edridge Lantern Test (ELT) as the standard for CVD detection and screening. Subjects who are able to correctly read all 14 plates of the Ishihara PIP (24-plate edition) will be classified as being CVN; those who cannot will be subjected to the ELT, in which the subjects need to identify all 18 color presentations correctly on their first attempt, following which they would be classified as being CVD but color safe. Those who did not meet the above criteria would be classified as CVD and color unsafe.

The Ishihara PIP is an inexpensive, portable, easily administered CVD screening tool which involves the identification of a colored number embedded in a background that differs only in color.[6] Till today, it remains the most widely used screening test for red-green CVD and multiple clinical trials have demonstrated its effectiveness,[2,17] with sensitivity of up to 99.0% when subjects had less than three errors.[3] However, the administration of the Ishihara PIP can be operator-dependent; variability in the lighting conditions, as well as instructions to the candidate, may produce variability and hence inaccuracy in the results.[8] Furthermore, the Ishihara PIP can be easily memorized by highly motivated individuals, which may not be uncommon among aircrew applicants who possess a strong desire to be selected for military aircrew training.[18] Another problem with the Ishihara PIP is that the test plates may show color degradation over time, requiring replacement at intervals to avoid inaccuracies in CVD screening.

The ELT was first developed in 1891[7] and involved an aperture illuminated by a light source which was fitted with colored glass slides and viewed from a distance of 15 ft. It has since evolved to become an electrically illuminated, funnel-shaped test lantern with rotating color discs in which subjects have to name accurately the colors presented. Over time, the color filters used in the ELT may fade, affecting its ability to present the colors and hence its sensitivity in accurately detecting CVD.

In July 2016, the Cone Contrast Test (CCT)[15] was introduced as part an operational trial to screen for CVD among applicants applying for aircrew positions in the RSAF. The CCT is a novel, computerized color vision test developed by Dr. Jeff C. Rabin and his team from the U.S. Air Force (USAF). It is a cone-specific contrast sensitivity test capable of providing a numerical score of color ability specific to the long- (L), medium- (M), and short-wavelength (S) cone functions, with the ability to categorize and quantitatively grade color deficiency in terms of severity,[14] administered through a forced-choice letter-recognition task. The CCT was performed for all applicants, in addition to the routine Ishihara PIP and ELT.

According to the USAF's Aeromedical Waiver Guide 2017, the CCT is now the only acceptable device to evaluate color vision for all USAF aircrew and applicants for flying positions; a CCT score of at least 75 points must be achieved for all cone types and for each eye before being classified as CVN. In contrast, the U.S. Navy's Aeromedical Reference and Waiver Guide allows for a combination of primary and secondary tests, which include the various PIP tests, Farnsworth Lantern test, and several computerized color vision tests (ColorDX, Color Assessment and Diagnosis, and CCT) to select for color-safe applicants as part of their aeromedical standards. A cut-off of 55 points on the CCT was the entry criteria for all aircrew applicants for the U.S. Navy.

Our study is a retrospective review that aims to evaluate the use of CCT as a color vision screening tool in an Asian population and compare these CCT outcomes with the Ishihara PIP–ELT screening pathway in identifying CVD in a cohort of aircrew applicants. As a secondary goal, our study aimed to compare and assess the impact to aircrew applicant attrition with the different CCT cut-off scores at 55 vs. 75. Lastly, we aimed to evaluate the repeatability of the CCT by comparing the scores between the left and right eyes for all aircrew applicants.

METHODS

Anonymized data from 862 aircrew applicants who underwent aircrew medical screening at the Singapore Aeromedical Centre for military aircrew selection from 21 July 2016 to 20 January 2017 were retrospectively analyzed by investigators of the Air Force Medical Service, RSAF. The study was exempted from a full Institutional Review Board review as it was an operational trial where anonymized data was collected as part of an audit.

All aircrew applicants underwent a complete ophthalmic examination and comprehensive color screening as part of standard entry requirements for military aircrew training. Ophthalmic examinations were comprised of best-corrected visual acuity, ocular motility, visual field testing, phoria and tropia assessments, and anterior and posterior segment examination under a slit-lamp. Color testing was performed in a standardized method, testing the right eye before the left and included the Ishihara PIP (24-plate edition): 14 red-green plates, passing score 14/14 correct in each eye; Edridge-Green Lantern Test (ELT) was performed on applicants who failed the Ishihara PIP: 18 presentations, passing score 18/18 correct in each eye; and the CCT, passing score: 75 in each eye on L, M, and S tests. Only one attempt was allowed for each eye for all three tests.

The computer-based CCT program presents a randomized series of 20 reddish (L), followed by greenish (M), then violet (S) letters visible to a single cone type in decreasing steps of cone contrast to determine the threshold for letter recognition. The CCT test was conducted monocularly in a dark room at 1 m and a single letter appeared briefly centered in the display, as shown in **Fig. 1**. The program randomly selected letters from those used on the ETDRS visual acuity chart[1] (H, N, V, R, U, E, D, F, P, Z; Arial bold font). Each letter appears briefly (1–1.6 s) on a gray background and the applicant was required to enter the letter they saw on a touch-screen letter pad. Applicants were required to provide an answer to all the letters. The time required for the test administration was approximately 3 min per eye. To allow for ease of interpretation for clinical application, the contrast sensitivity scores are graded on a 100-point scale (each letter entered correctly scored 5 points) for each cone in each eye. The CCT score for each eye was pegged to the cone type with the lowest score, and the overall CCT score was pegged at the lower score for either eye.

We collected data on the incidence of CVD and attrition rates when employing the CCT and Ishihara PIP–ELT combination as screening pathways. Our study also analyzed the repeatability of the CCT by comparing the CCT scores of the right and left eyes of the same subject measured as the coefficient of repeatability (COR). Subjects with COR that differed by 15 points or more were considered to be outside normal limits.[15]

RESULTS

The mean age of the 862 aircrew applicants was 20.3 yr (SD ± 2.3), with 823 men and 39 women. All applicants had best-corrected visual acuity of 20/20 or better and there was no significant ocular pathology found in all 862 aircrew applicants.

A total of 17 (1.97%) male aircrew applicants failed the Ishihara PIP test. Following ELT, 11 applicants were assessed to be color safe. Only six male applicants were assessed to be color unsafe for flying following the ELT, leading to a final attrition rate of 0.7%. Of note, all 17 male applicants who failed the Ishihara PIP test did not achieve an overall CCT score of at least 75. Of those 17 applicants, 16 had a CCT score of $<$55 while the remaining applicant had a CCT score of 60 (**Table I**).

When we analyzed the CCT results, there were a total of 26 (3.02%) applicants who failed to achieve a CCT score $\geq$75 (5 protan, 21 deutan). Of these applicants, 17 (1.97%) had failed to achieve a CCT score of $\geq$55 (5 protan, 12 deutan). Of these 17 applicants who obtained a CCT score of $<$55, 16 of them failed the Ishihara PIP test. The only applicant who passed the Ishihara PIP test had a CCT score of 50. All 26 applicants who obtained a CCT score of $<$75 did so due to deficiencies in the L or M cones (corresponding to cones maximally sensitive to red and green wavelengths, respectively). None of the subjects had deficiencies in the S cone (corresponding to cones maximally sensitive to blue wavelengths).

Of note, all the applicants who were unable to obtain a CCT score of $\geq$75, or had failed the Ishihara PIP, were all male subjects. All the female subjects passed the Ishihara PIP and had a CCT score of $\geq$75.

We analyzed the attrition rates for the various color vision screening pathways using the Ishihara PIP, the Ishihara

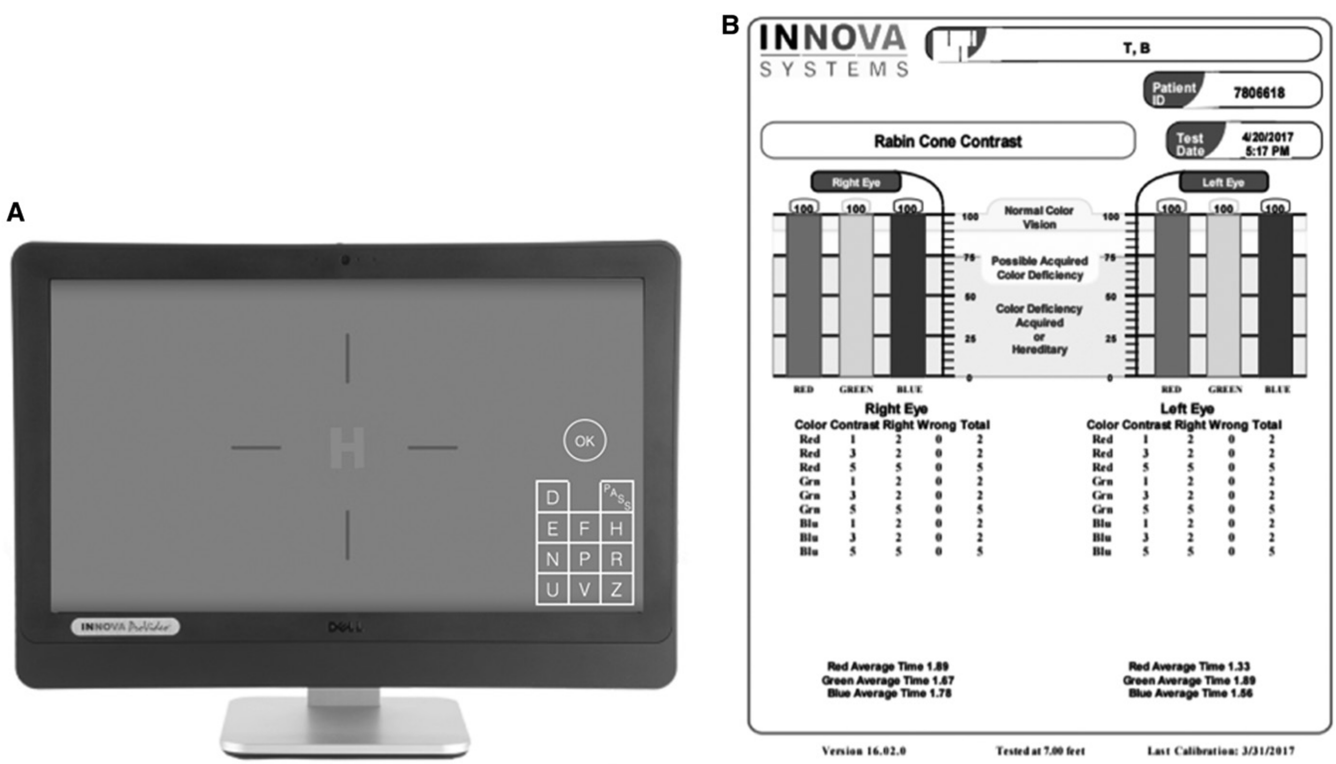

Fig. 1. A.) Screen with single colored letter presented to the applicant. B.) Test scores automatically generated by the CCT program upon conclusion of the test.

Table I. Comparison of Ishihara PIP Results and CCT Score.

OVERALL CCT SCORE	FAILED ISHIHARA PIP	PASSED ISHIHARA PIP	TOTAL
0–50	16	1	17
55–70	1	8	9
75–100	0	836	836
Total	17	845	862

PIP: pseudo-isochromatic plates; CCT: Cone Contrast Test.

PIP and ELT, and the CCT (both cut-offs of ≥55 and ≥75). Of note, the attrition rates for the Ishihara PIP and CCT ≥55 were identical at 2.0%, with both sets having similar applicants in 16 out of the 17 cases. Using the ELT in addition to Ishihara PIP decreased the attrition rate to 0.7% while having the CCT passing score at ≥75 increased the attrition rate to 3.0%. **Fig. 2** shows the attrition rate of the various tests when employed as the primary color vision screening modality.

Out of our cohort of 862 aircrew applicants, 847 (98.3%) showed interocular (right vs. left eye) differences in score of <15 and 15 (1.7%) showed differences in score of ≥15. Of the 15 applicants with an interocular difference in score of ≥15, 14 were identified as CVD with a CCT score <75 and only 1 applicant was classified as being CVN. There was a statistically significant difference in the COR between CVD and CVN applicants (Fisher's exact test; $P < 0.01$). Of 836 CVN applicants, only 1 applicant had a COR of ≥15. In comparison, both the Ishihara PIP test and ELT were found to have a 100% concordance of pass/fail status between the right and left eye across all applicants.

DISCUSSION

In today's context, the need for good color vision among military aviators remains an important prerequisite to their safe and effective handling of in-flight tasks, some of which may be time-critical in nature. The increasing use of multicolored multifunctional displays (e.g., terrain maps, weather displays, etc.) in our fourth and fifth generation aircraft, which contribute to pilot overall situational awareness and decision-making processes, necessitate that only aircrew with normal color perception are selected for military flying duties in order to ensure flight safety and mission success. The need to ensure more accurate detection and classification of color vision deficiency in our aircrew applicants remains an important task and a key area of research for military aviation medical practitioners.

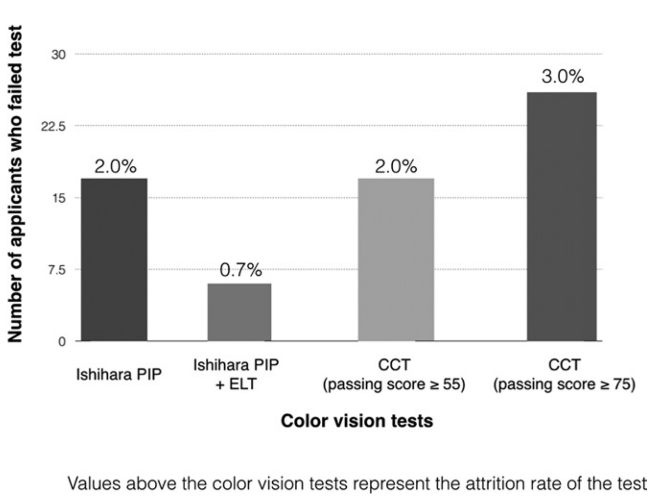

Fig. 2. Comparison of attrition rate between tests.

Prior to the introduction of the CCT, we used the Ishihara PIP–ELT combination as the color vision screening pathway for all aircrew applicants. The end-point was the identification of color-safe applicants based on their ability to accurately differentiate red, green, and white lights, colors which were widely used and deemed critical in military aviation operations. However, as the context in aviation has changed with an increased use of multifunctional displays with multicolored symbology, the need for military aviators to distinguish multiple colors accurately and expeditiously is critical.[16]

The ideal color vision screening test should have the characteristics of good sensitivity and specificity as well as excellent test repeatability. To prevent motivated applicants from memorizing the answers to the screening test using noncolor dependent visual cues, the use of random presentations should be incorporated into the test. The screening test should also be fast and easy to administer for improved acceptability by aircrew applicants. Based on our experience, the CCT had all of the above characteristics; in addition, the CCT was also able to reliably specify the type of color vision deficiency and quantify its severity.

In their pilot CCT study involving 1446 pilot applicants, Rabin et al. demonstrated complete sensitivity (1.0) in agreement with the anomaloscope for the detection and categorization of CVD and specificity for confirming CVN of 1.0 for L and M cones and 0.98 for S cones.[15] In another prospective study of 65 CVD and 68 CVN subjects, Walsh et al. evaluated seven color vision tests (four PIP tests, one lantern test, and two computerized tests) to determine a suitable screening test which could be employed by the U.S. Army.[18] The authors found that the CCT demonstrated high sensitivity (0.97) and specificity (0.96) in both eyes with no significant difference when compared with the Oculus anomaloscope, classically regarded as the "gold standard" in color vision testing. When compared to another computerized color vision screening test—the Color Assessment and Diagnosis test—the CCT was found to have greater sensitivity and specificity (>0.90 compared to >0.85 for the Color Assessment and Diagnosis test) and had a significantly faster administration time. In another prospective study of 38 subjects with CVD (10 subjects with protanopia and 28 subjects with deutanopia determined by the Neitz anomaloscope OT-II) and 9 CVN subjects (age and gender matched) by Fujikawa et al., the CCT demonstrated sensitivity and specificity of 1.0 in diagnosing the CVD and specifying its type.[9] These studies validated the excellent sensitivity and specificity of the CCT. Note that all three studies defined CVN as when the CCT score was 75 or greater.

In the absence of ocular pathology in both eyes, the interocular differences in color perception based on CCT for CVN individuals may reflect test-retest variability. Rabin et al. reported a calculated L, M, and S COR of 15 points, suggesting that scores that differed by 15 points or more, when measured in the same CVN subject over time or when comparing right and left eyes are considered outside normal limits.[15] In our study, we found 15 applicants who had COR of ≥15 points, of whom 14 were from the CVD group (CCT score < 75) and one from the CVN group. Our results demonstrated excellent interocular test repeatability of 99.9% in CVNs (835 out of 836 CVN applicants).

Among our CVD population ($N = 26$), there was a near equal distribution of those with a COR of ≥15 points (53.8%, $N = 14$) and those with a COR of <15 points (46.2%, $N = 12$) with a mean COR of 15.4 points (SD ± 11.0). Of the 14 CVD applicants with COR ≥15 points, the mean COR was 23.6 points (SD ± 7.9) with 42.9% of them ($N = 6$) achieving a higher CCT score in the left eye compared to the right. This distribution among the CVD population could be due to reasons such as: 1) learning effect: applicants may be unsure of what to expect on their first attempt, resulting in a poorer result for the first eye tested; 2) inattention: despite the entire CCT only taking 6 min, there is a potential for applicants to have lapses in their attention during the duration of the test; 3) guesswork: as a forced choice letter-recognition task, CCT presents applicants with a 1 in 10 chance of getting the correct answer despite not being able to see the depicted colored letter; 4) letters with different legibility (e.g., Z is more easily discernible than E and F or U and V), especially at contrast threshold; and 5) subtle ocular pathology in one of the eyes not picked up during the rest of the ophthalmic examination. The authors believe that the main reason for the near equal distribution of COR of ≥15 or <15 points is a result of guesswork by motivated applicants.

Our results suggest that the Ishihara PIP allows for more applicants to be selected compared to the CCT (with a passing score of ≥75), with eight applicants passing the Ishihara PIP test but only scoring 55–70 points on the CCT. This result is similar to that reported by Rabin et al., who reported poorer sensitivity in color deficiency in individual PIP (Dvorine, Standard Pseudoisochromatic Plates Part 2, and Farnsworth F2 plate) and combined PIP tests.[15] In contrast, Walsh et al. reported good sensitivities in color deficiency of the Dvorine PIP and Pseudoisochromatic Plate Ishihara Compatible tests, with no statistically significant difference between the PIP tests and the anomaloscope. We postulate that these eight applicants were likely to have mild CVD. As such, in only accepting applicants with a CCT score of at least 75, those with mild CVD will be safely excluded. This is significant in our context of aircrew selection and substantiates the need to enforce stricter color vision standards by maintaining a CCT passing score of ≥75.

Our study generally showed great similarity between the Ishihara PIP and the CCT with a passing score of ≥55. Hence, in the absence of the CCT, the Ishihara PIP may be a reasonably accurate color vision screening tool comparable to the CCT with a passing score of ≥55. It is highly likely that all 18 applicants who either failed the Ishihara PIP or scored less than 55 points on the CCT had significant CVD. Although there was a very strong concordance between the Ishihara PIP and CCT score of ≥55, the lack of complete concordance between the two screening methods was likely due to test-to-test variability and/or the possible memorization of the Ishihara PIP by motivated applicants.

Introduced in 2017, the ColorDx CCT-HD test (Konan Medical USA Inc., Irvine, CA) is an improved version of the original CCT, designed in collaboration with the USAF School of Aerospace Medicine, Operational Based Vision Assessment Team. The ColorDx CCT-HD test aims to further differentiate individuals with CVN by increasing the range of very low contrast testing (approximately 0.25%) using high-precision color displays. In the authors' opinion, while such differentiation allows better quantification of color vision and may have applicability in the clinical setting, the impetus for introducing the ColorDx CCT-HD test to immediately replace the CCT for screening of military aircrew applicants may not be as urgent or necessary. As a color vision screening tool, the CCT is able to accurately detect individuals with CVD to be excluded from military aircrew training.

The prevalence of congenital CVD in the general population is often cited to be 8% among males and 0.4–0.5% among females.[11,12] Our study observed that all 26 subjects who got a CCT score less than 75 only had deficiencies in the L or M cones (corresponding to cones maximally sensitive to red and green wavelengths, respectively), with none having deficiencies in the S cone (corresponding to cones maximally sensitive to blue wavelengths). This is consistent with the epidemiology of congenital color vision deficiency. The prevalence of congenital red-green color deficiency in an Asian population has been reported to range from 4–6.5% in males and 0.4–1.7% in females.[4] Blue-yellow color deficiency is much less common, with a reported prevalence of 0.008%;[12] it may be inherited as an extremely rare autosomal dominant or recessive disorder, however, it is often an acquired condition due to organic eye pathology, and is expected to be uncommon in the generally young and healthy aircrew applicant population.

Our study found that 26 out of the 823 male applicants (3.2%) had a CCT score less than 75, which is slightly lower than the reported Asian prevalence of 4–6.5% in males.[4] This is likely due to the self-selecting nature of the aircrew applicant population where individuals with known CVD were less likely to apply to be an aircrew.

The CCT is an effective modality for color vision testing with excellent sensitivity and specificity, good test repeatability, and is fast and easy to administer. Our study demonstrated a high correlation between the CCT with a passing score of ≥55 and the Ishihara PIP. Employing the CCT with a passing score of ≥75, instead of the Ishihara PIP–ELT combination, as the screening pathway to identify CVD applicants would lead to an increase in attrition rate of 0.7–3.0%. This, however, would ensure that only aircrew with normal color perception are recruited for military flying duties, ensuring flight safety and mission success.

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