A Computer-Based Farnsworth-Munsell 100-Hue (CFM-100) Test in Pilots' Medical Assessments

Yinjuan Zhang; Jin Ma; Shan Cheng; Wendong Hu

OBJECTIVES: This study investigated the effectiveness and identified the cutoff values of the computer-based Farnsworth-Munsell 100-Hue (CFM-100) test for screening color vision deficiencies in the pre-employment examination of civil aviators in China.

METHODS: Firstly, subjects were stratified into normal, color weakness, and color blindness with the Ishihara pseudoisochromatic plate test (IPPT) by two ophthalmologists. Then they randomly completed CFM-100 and Farnsworth-Munsell 100-Hue (FM-100) tests. Total error scores (TES) and the time taken for the CFM-100 and FM-100 were analyzed and the cutoff values for the CFM-100 were determined.

RESULTS: Of 218 subjects, 159 were normal while 59 were diagnosed with dyschromatopsia. The TES of the CFM-100 were congruent with those of the FM-100 (20.0 ± 18.8 vs. 20.6 ± 17.7, 160.9 ± 66.0 vs. 151.1 ± 66.4). The testing time for the CFM-100, however, was less than the FM-100 (10.3 ± 2.8 min vs. 12.9 ± 2.9 min, 7.8 ± 2.5 min vs. 12.6 ± 3.3 min). The correlation coefficient R was 0.93 and Cohen's kappa was 0.89 for the two methods. Further analyses defined 34 as the cutoff value to differentiate excellent from fair color discrimination (sensitivity 58.0%, specificity 94.7%) and 101 as the cutoff value to judge fair vs. poor (sensitivity and specificity both 98.8%) for the CFM-100. The cut-off value was 72 for distinguishing normal from defective color vision (sensitivity 96.6%, specificity 98.7%) and 110 was for distinguishing color weakness from color blindness (sensitivity 97.6%, specificity 97.7%) for the CFM-100.

CONCLUSIONS: The CFM-100 is an effective method for the diagnosis of dyschromatopsia with high sensitivity in screening airline pilots.

KEYWORDS: color vision, Farnsworth-Munsell 100-Hue, computer-based Farnsworth-Munsell 100-Hue, pilots.

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Color vision is an important part of visual functions and plays a critically indispensable role in identifying information and detecting signals in aviation work.[2,3] The aviator relies on color signals to distinguish the position of the runway and identify various instruments, obstacles, signal lamp information, etc., especially during red-eye flights. Thus, the examination of color vision is essential for the safety of aviation.[1]

Color vision deficiency (CVD), or color blindness, is the inability or decreased ability to distinguish different colors under normal lighting conditions,[19] which is one of the most common disorders of vision, with an incidence that varies from race to race and from country to country. The prevalence of red-green color deficiency is between 4% and 6.5% in men of Chinese and Japanese ethnicity.[5] However, most color-blind cases remain undetected due to the absence of proper screening.

The Ishihara pseudoisochromatic plate test (IPPT) is the most popular method to screen color vision deficiency worldwide.[2,3] Individuals who pass the IPPT are considered to have normal color vision, while those who fail the test are asked to take secondary tests to confirm the diagnosis of color vision deficiency. Through years of practice, the IPPT has been proven to be very advantageous for quick screening of a large-scale population for color vision deficiency. However, since the IPPT

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only subjectively reveals normal or abnormal color vision, it cannot accurately evaluate the severity of any abnormalities.[10] More importantly, individuals with color vision defects sometimes may pass the test by ‘memorizing’ the correct answers for every plate in advance. Taken together, it seems essential to explore other effective and convenient methods to supplement current color vision testing protocols.

The Farnsworth-Munsell 100-Hue (FM-100) was devised by American psychologists in 1943 and contains 85 caps which are recorded on a specific record sheet according to the arrangement number of the test-takers. Subsequently, the error score is calculated and an error score diagram is constructed. This examination method is a psycho-technical arrangement test with high sensitivity to enable the quantitative and qualitative determination of the color discrimination ability of individuals and also detect attenuation of color vision with increasing age.[11,13] However, the operation of the test is complex and it takes a long time to obtain results. In addition, the apparatus is inconvenient to carry around and easily discolored after several tests.[8,14] Therefore, it is imperative to explore rapid and effective methods for the examination of color vision.

A computerized ophthalmic examination system has been designed which achieved consistency with the traditional color blindness diagram using chroma adjustment to detect color vision defects. This instrument digitally applied the conventional visual and color vision examination method by computer, but failed to examine color vision quantitatively.[17] In the present study we designed a color vision system, a computer-based Farnsworth-Munsell 100-Hue (CFM-100) test, which was developed by Unity 3d Integrated Development Environment (IDE) and programmed using Java, to provide a quick and accurate method for screening color vision abnormalities in potential aviator candidates.

METHODS

Subjects

All subjects were selected from three colleges and universities in the age range 20 to 24 yr after a poster recruitment campaign in China. Subjects were required to have an uncorrected visual acuity of >0.5 without any ophthalmic or psychological disease. The purpose and procedure of the study were explained to subjects who provided signed consent forms before the testing commenced. Subjects were not allowed to use sunglasses or contact lenses. The study protocol was approved by the Human Research Ethics Committee of the institution (No. SZFYIEC-YJ-2020-38).

Materials

***IPPT*.** The IPPT was first created by Ishihara in Japan in 1916 and, since then, it has been used internationally as the examination of choice for identifying congenital dyschromatopsia, providing a high diagnosis rate.[10] The test consists of 38 Ishihara plates, each of which are filled by numerous circled dots that seemingly spread in a randomized fashion with different colors and sizes. However, they are arranged in the form of numbers or shapes clearly visible to those with normal color vision, but invisible or difficult to see for those individuals with color vision defects. Even though the full test consists of 38 plates, if a severe deficiency in trichromacy exists, the diagnosis usually becomes apparent after reading only a few plates.[4,7,16] Besides, the subjects are only allowed to take 3 s to give the answer for each plate, which is positioned at a distance of 70 cm and a 45° angle from the test-taker.

***FM-100*.** The FM-100 belongs to the color dispensing method, which was developed by selecting the standard Munsell color spectrum based on the color principle,[20] and uses points with different hues on a similar color ring in the luminance-matched CIE chromaticity diagram to form a color disc mixed with 8 fixed hues and 85 movable hues dividing into 4 boxes. The examinee is required to rank caps in each box for 2 min according to the regular order of hue changes. The investigator records the ranking results, then calculates the error score to determine the type and severity of abnormal color vision of the examinee.[12,21]

***CFM-100*.** The CFM-100 is composed of four rows of caps with very small color differences. The first row is red-yellow, the second row is yellow-green, the third row is green-blue, and the fourth row is blue-red. The hue of a total of 95 caps forms a complete color ring and the 95 caps differ from each other with a chroma lightness value (H) of 2 units. The chroma (B) and saturation (S) remain essentially unchanged, which can be expressed as 5/5 according to the Munsell color system calibration method[15] (**Fig. 1**). Each row has 2 fixed caps and the remaining 85 are movable, so the test-takers can move any cap at will, but only within its own row, by dragging the cap with the computer mouse (**Fig. 2**). After entering the test, the examinee first filled in personal basic information, then watched the instruction played automatically, and started the

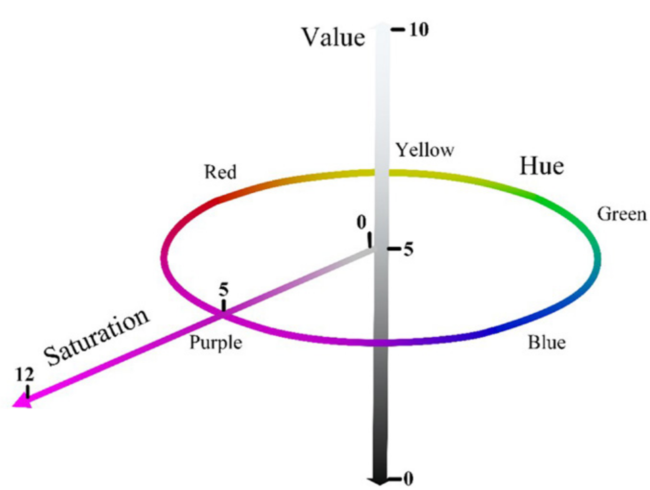

Fig. 1. The color system of CFM-100. [Please see the article online (https://doi.org/10.3357/amhp.5943.2022) for a color version of this figure.]

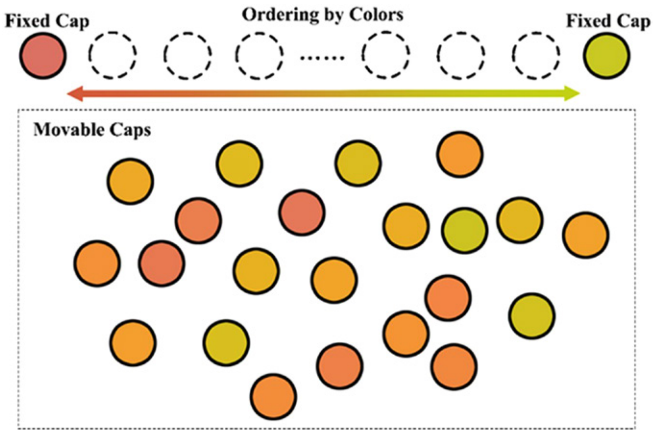

Fig. 2. The operation diagram of CFM-100. [Please see the article online (https://doi.org/10.3357/amhp.5943.2022) for a color version of this figure.]

test. Four rows of colors are randomly displayed in the test interface each time. The test-taker moves each cap in the order of gradual changes in the surface colors according to his/her assessment of the caps' chromas. The test requires 10–15 min to complete and the examinee is reminded of the time limit, but it is not necessary to terminate the test due to the examinee exceeding the time limit.[15]

Procedure

All subjects were first tested with IPPT and then, based upon the results from the plate reading, were categorized into a normal color vision group, a mild color vision deficiency group, or a color blindness group by two ophthalmologists. Furthermore, the three groups were examined again randomly using both the FM-100 and CFM-100. For test-taking, a subject in the FM-100 was at a 60° angle. In order to familiarize with the test procedure, initial trial testing for 5 min was conducted for each examinee. Subjects taking the CFM-100 were required to be 50 cm away from the computer display. The color temperature of the display was 6500 k and the brightness was 250 cd · m^{-2}, with high color accuracy ($\Delta < 3$) and wide color gamut (≥99% of NTSC), and color calibration was conducted by Datacolor SpyerX regularly to make it present the real color accurately. Routinely, all subjects knew that the test time was 10–15 min. Before sitting the formal tests, subjects were allowed to practice freely for 5 min and the two tests were separated by 20 min to avoid an interaction between the tests and asthenopia caused by the previous test.

Statistical Analysis

All data were analyzed using SPSS version 17.0 software. The results are presented as the mean ± SD. A paired *t*-test was employed to compare differences between the two methods. Pearson's correlation coefficient and scatter plots were used to determine the relationship between the FM-100 and CFM-100. The Kappa coefficient was analyzed to indicate the internal consistency between the classification of color vision defects for the FM-100 and CFM-100. The cutoff values were determined by ROC curve analysis. $P < 0.05$ was considered to be a statistically significant difference.

Table I. Test Results of the Subjects.

ITEM	DYSCHROMATOPSIA	NORMAL COLOR VISION
Demographic		
Age (yr)	22.59 ± 1.68	21.43 ± 2.53
M:F	58:01	97:62
FM-100		
Test Score	150.73 ± 66.95	19.84 ± 17.54
Color discrimination		
Excellent	0	75
General	10	83
Poor	49	1
Types of color vision defects		
Red abnormal	40	–
Green abnormal	19	–
CFM-100		
Test Score	160.51 ± 66.47	19.40 ± 18.45
Color discrimination		
Excellent	0	73
General	11	85
Poor	48	1
Types of color vision defects		
Red abnormal	41	–
Green abnormal	18	–

RESULTS

A total of 218 subjects were enrolled in the study with an age range of 20 to 24 (22.4 ± 1.46) yr. The study included 159 subjects with trichromacy (M:F = 97:62), 17 with a mild color vision deficit, and 42 with dyschromatopsia (M:F = 58:1). Based upon the test results of the FM-100, 159 subjects possessed normal color vision, which further stratified as 75 with strong, 83 with fair, and 1 with a poor color discrimination capacity. However, in the group of 59 abnormal color vision, 10 had fair color discrimination capacities, while 49 had poor color discrimination, of whom 40 were diagnosed with protan color blindness and 19 with deutan color blindness. Following the results from the CFM-100 of 149 with normal color vision, 73 had strong, 85 fair, and 1 poor color discrimination. Of the 59 with dyschromatopsia, 11 had fair color discrimination and 48 poor color discrimination; 41 were further classified as protan and 18 as deutan (**Table I**).

The subjects with normal color vision achieved lower scores than those with abnormal color vision. For subjects with normal color vision, their average total error scores (TES) with the CFM-100 were not significantly different from those obtained with the FM-100 ($P > 0.05$); the former test took less time than the latter, and this difference was statistically significant ($P < 0.05$). The scores of subjects with abnormal color vision appeared to be greater with the CFM-100 than those obtained using the FM-100, but the difference did not reach statistical significance ($P > 0.05$). In contrast, the former test required less time than the latter, with the

Table II. Comparison of the Test Results Between FM-100 and CFM-100 for Subjects with Normal and Abnormal Color Vision.

	NUMBER OF CASES (*N*)		SCORE (`X ± S)		TIME (`X ± S)(min)	
SUBGROUP	NORMAL	ABNORMAL	NORMAL	ABNORMAL	NORMAL	ABNORMAL
FM-100	159	59	19.40 ± 18.45	150.73 ± 66.95	12.96 ± 3.05	12.64 ± 3.28
CFM-100	159	59	19.84 ± 17.543	160.51 ± 66.47	11.05 ± 2.97	7.73 ± 2.49
t-value			$t = -0.333$	$t = -1.815$	$t = 7.025$	$t = 9.882$
P-value			$P > 0.05$	$P > 0.05$	$P < 0.01$	$P < 0.01$

difference being statistically significant ($P < 0.05$) (**Table II**). Pearson's correlation for TES with the FM-100 and CFM-100 was 0.93 ($P < 0.05$) (**Fig. 3**).

The test results of the FM-100 for color vision defects were abnormal in 40 cases for red defects and 19 cases for green defects, while the test results of the CFM-100 for color vision defects included 41 cases of red defects and 18 cases of green defects. The CFM-100 mistook 1 person with red defect as green defect and two people with green defect as red defect. The remaining 39 cases for red defects and 17 cases for green defects were consistent with the FM-100. The consistency analysis on the results of classification of color vision defects performed using the FM-100 and CFM-100 revealed that the two test methods had high consistency with a coefficient of agreement (Cohen's kappa) of 0.89.

Based upon the cutoff scores of 20 for superior vs. average and 100 for average and poor color discrimination from the FM-100, the cutoff score for superior vs. average and poor color discrimination was 34 (sensitivity 58.0%, specificity 94.7%) and for poor vs. superior and average color discrimination was 101 (sensitivity 98.0%, specificity 98.8%) with the CFM-100. Furthermore, the sums of sensitivity (58.0%) and specificity (94.7%) for the value of 34 reached a maximum of 1.527, while the sums of wrong and missed diagnosis rates had a minimum of 0.473. The sums of sensitivity (98.0%) and specificity (98.8%) for the value of 101 were the largest (1.968), and the sums of wrong and missed diagnosis rates were the smallest (0.032) (**Table III**).

According to the IPPT, the qualitative cutoff values for color discrimination for the CFM-100 was 72 for differentiating normal from abnormal color vision, and 110 for differentiating color weakness from color blindness. Moreover, for the value of 72, the sums of its sensitivity (96.6%) and specificity (98.7%) was the greatest (1.954), and the sums of the wrong rate and missed diagnosis rates the smallest (0.046). When 110 was the cutoff point between color weakness and color blindness, the sums of its sensitivity (97.6%) and specificity (97.7%) were the greatest (1.949) and the sums of the wrong and missed diagnosis rates the smallest (0.051) (**Fig. 4**).

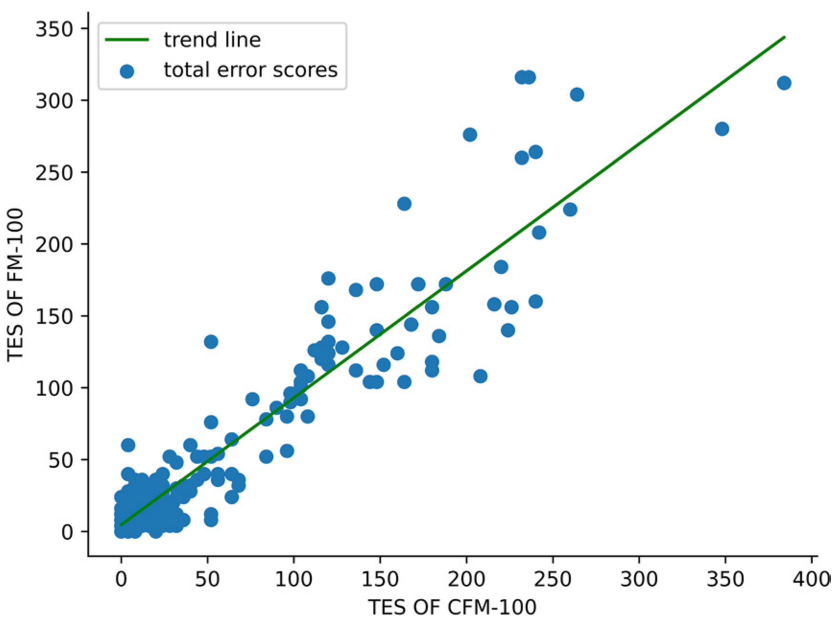

Fig. 3. Correlation curves of FM-100 and CFM-100 scores. [Please see the article online (https://doi.org/10.3357/amhp.5943.2022) for a color version of this figure.]

DISCUSSION

The CFM-100 was designed based upon the principle of the FM-100, which detects the degree and type of color vision defects through the ranking results of color caps.[10,20] Data for colors in the CFM-100 were obtained from the FM-100 by a color monitoring instrument, then converted using L*a*b of CIE into R*G*B through a formula, and then presented on the computer.

In our study, the TES of the FM-100 and CFM-100 were not found to be statistically significantly different, providing evidence that the two methods are consistent for the evaluation of color vision abnormalities. Furthermore, Pearson's correlation analysis suggests that the results of the two methods are linearly correlated, and the internal consistency analysis of the scores between the two methods further shows that the consistency of the two methods is significant with a Cohen's Kappa of 0.89. In addition, the test taking time for the CFM-100 and FM-100 was also analyzed and revealed that the test time of the former is significantly shorter than the latter. Therefore, the CFM-100 is not only comparable to the FM-100, but also overcomes the limitations of the FM-100, as well as improving the detection efficiency for accurate color vision.

Taking the FM-100 as the reference, the cutoff points of the CFM-100 derived from the ROC curve were 34 and 101 for differentiating test-takers with superior color discrimination from average, and average from poor, which upheld high specificity. However,

Table III. Classification of Cut-Off Values of Color Discrimination Ability and Color Vision Types of CFM-100.

	CUTOFF VALUE	SENSITIVITY (%)	SPECIFICITY (%)
Division of color discrimination ability			
Excellent, fair and poor color discrimination	34	58	94.7
Poor and excellent color discrimination and general	101	98	98.8
Color vision type division			
Normal and defective color vision	72	96.6	98.7
Color weakness and color blindness	110	97.6	97.7

the sensitivity of the cutoff value of 34 was 58.0%, which might be related to the fact that the subjects were college students, the majority of whom inherited good color vision, which gave rise to lower scores. Therefore, CFM-100 could achieve a quick and accurate diagnosis of the color discrimination ability of test-takers such that the system could help to select a part of the population with excellent color discrimination ability for special occupations and professions such as aviators.

According to the qualitative results of the subjects based on the IPPT, the critical value of the CFM-100 for judging the type of color vision was investigated.[9,18] The results revealed that 72 was the cutoff value for differentiating normal from color vision defects, with a high sensitivity and specificity, while 110 was defined as the cutoff value for differentiating color weakness and color blindness, with a high sensitivity and specificity. Therefore, the CFM-100 could accurately determine normal and defective color vision, and subsequently

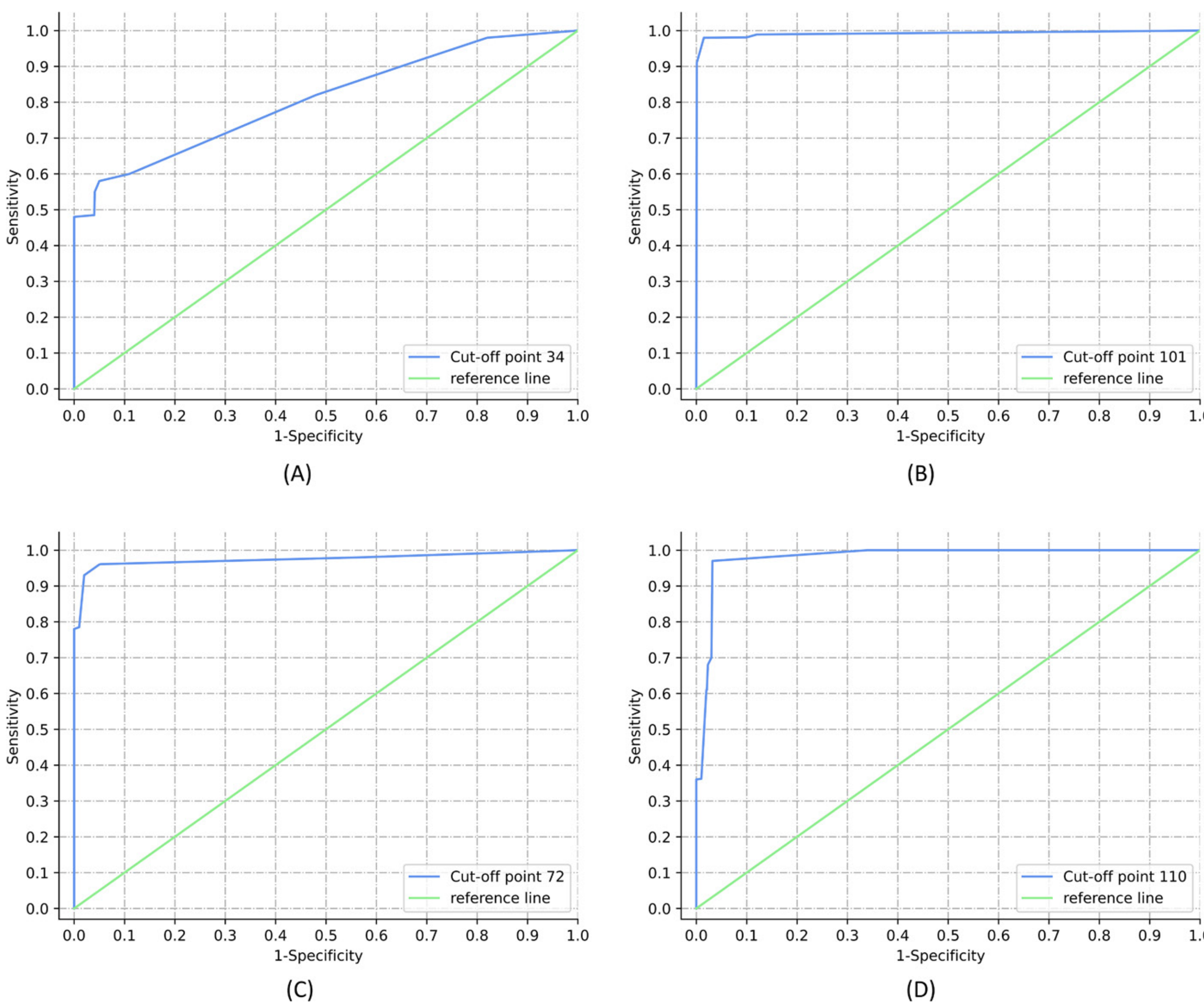

Fig. 4. ROC curve for CFM-100. A) Cutoff point 34; B) cutoff point 101; C) cutoff point 72; and D) cutoff point 110. [Please see the article online (https://doi.org/10.3357/amhp.5943.2022) for a color version of this figure.]

improve the accuracy of color vision examinations. At the same time, the degree of color weakness could be judged according to the cutoff value by selecting test-takers with less color weakness among the abnormal color vision group to continue the next test on color vision adaptability in the aviation environment.[6,13]

In conclusion, the CFM-100 is beneficial for reducing the error of color vision assessment of aviation personnel and improving the accuracy of color vision examinations. It can quantitatively determine the degree of color weakness, thereby providing the basis for perfecting further testing, which will help to optimize the selection criteria for aviators and improve their color vision inspection levels. Furthermore, the CFM-100 can be installed on other computers with top color configuration mentioned in the study and it would be easy to transport, with excellent consistency in the results, such that it truly fits into the requirements for aviation personnel recruitment and other examination demands.

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