e-ISSN: 0975-9506, p-ISSN: 2961-6093

Available online on www.ijpqa.com

International Journal of Pharmaceutical Quality Assurance 2025; 16(12); 95-99

Original Research Article

Correlating Cone Function and Hue Discrimination: Structural and Functional Insights from the FM100 Test

Gupta C.[1], Hada R.[2], Sharma P.[3], Vyas S.[4], Gupta V.[5]

[1]Assistant Professor, Upgraded Department of Physiology, SMS Medical College, Jaipur, Rajasthan, India

[2]Associate Professor, Upgraded Department of Physiology, SMS Medical College, Jaipur, Rajasthan, India

[3]Assistant Professor, Upgraded Department of Physiology, SMS Medical College, Jaipur, Rajasthan, India

[4]Senior Professor, Upgraded Department of Physiology, SMS Medical College, Jaipur, Rajasthan, India

[5]Professor, Upgraded Department of Physiology, SMS Medical College, Jaipur, Rajasthan, India

Received: 25-09-2025 / Revised: 23-10-2025 / Accepted: 26-11-2025

Corresponding Author: Dr. Chhaya Gupta

Conflict of interest: Nil

Abstract:

Introduction: Colour vision serves as a critical indicator of cone photoreceptor function and offers valuable complementary information to assessments of spatial visual performance, such as best-corrected visual acuity (BCVA), contrast sensitivity and inherited and acquired retinal disorders.

Aim & Objectives: 1. To investigate the relationship between cone photoreceptor function and hue discrimination ability using the Farnsworth-Munsell 100 Hue Test (FM100). 2. To explore the potential of the FM100 Hue Test as a clinical tool for detecting and monitoring cone-related retinal dysfunction.

Material & Methods: An Observational, Cross-sectional research study was systematically conducted in the Physiology department in association with the Ophthalmology department in SMS Medical College, Jaipur, to assess the prevalence and characteristics of colour vision deficiency (CVD) among 170 medical students. Participants were screened for CVD using the Ishihara pseudoisochromatic plates and further evaluated using the Farnsworth-Munsell 100 Hue (FM100) Test to assess hue discrimination ability. All collected data were systematically entered and organized in tabular form. A p-value of <0.05 was considered statistically significant.

Result: A total of 170 medical students (age range: 18- 25 years; mean age: 21.5± 2.45 years) were included in the final analysis. Revealed significant variation in Hue discrimination ability in Medical students. The result exhibits Mean Box specific Error Score (ES) and Mean Total Error Score (TES) were significantly elevated.

Conclusion: This study's findings support the application of the FM100 Hue Test as a sensitive tool for evaluating functional aspects of cone-mediated vision, particularly in clinical and occupational screening settings.

Keywords: Colour Vision Defects (CVD), Farnsworth-Munsell (FM) 100 Hue Test, Hue Discrimination, Ishihara pseudo isochromatic test, Medical students, Total Error Score (TES).

Introduction

Vision serves as a primary modality for perceiving external stimuli and assimilating information in daily human experience. The neural underpinnings of colour vision are highly complex, encompassing the integrated functions of diverse cellular components, including retinal photoreceptors, bipolar and ganglion cells, neurons within the lateral geniculate nucleus, and multiple hierarchical processing levels of the visual cortex. [1]

Colour vision research spans multiple fields—from neuroscience and genetics to psychophysics, imaging, and design. Because colour perception is both complex and inherently subjective, its study remains challenging yet highly engaging. This overview of the special issue 'Colour: Cone Opponency and Beyond' summarises current insights in colour science and outlines key questions that remain open in the field. [2]

Red, yellow, green, and blue hold a central place in both colour perception and language. In vision science, they are considered “unique hues” because they represent pure chromatic sensations that cannot be broken down into other colours. All other hues can be described as mixtures of these perceptual primaries. These unique hues form two opponent pairs—red versus green and blue versus yellow—alongside the achromatic pair, black and white. [3] Retinal ganglion cells transmit colour signals to the

brain, where the retina and lateral geniculate nucleus use opponent-processing mechanisms to refine chromatic distinctions. In the visual cortex, features such as contrast, hue, and colour constancy are integrated to form a coherent percept of the visual world. This coordinated system enables rapid and accurate colour perception, supporting efficient responses to changing environments. [4]

Recent advances in our understanding of early-stage processing within the retina and thalamus have provided new perspectives on cortical mechanisms of colour perception. Emerging evidence suggests that colour is not processed in isolation but rather in conjunction with luminance and visual form, through shared neural circuits. This integrated processing appears to contribute to a unified and robust representation of the visual environment. [5]

Vision is a primary human sense, shaped by an evolutionary shift from early dichromatic sight to trichromacy about 30 million years ago through opsin gene diversification. This adaptation allows humans to perceive black, white, and the full range of red, green, and blue hues. Colour discrimination arises from coordinated processing between the retina and the brain, transforming light reflected from objects into neural signals that travel through a complex pathway to the visual cortex. [6]

Rhodopsin, the key visual pigment in photoreceptor cells, is a modified form of vitamin A with a conjugated π-electron system that enables light absorption. It consists of the protein scotopsin bound to the chromophore retinal, which attaches to a lysine residue through a protonated Schiff base. This linkage forms the molecular foundation of rhodopsin's light-sensitive function. [7] Beyond identifying colour vision defects, the Farnsworth–Munsell 100 Hue (FM100) test is useful for assessing colour discrimination in various medical conditions. It can track changes over time and detect subtle deficits linked to disease. Reported sensitivity and specificity range from 100%/83% to 89%/100%, demonstrating its reliability for clinical evaluation of chromatic function.[8]

In the present study, we assess colour discrimination that quantifies global performance by reporting the Total Error Score (TES) value of the Farnsworth–Munsell 100-Hue test, a renowned and excellent grading testing method for assessing colour discrimination that quantifies global performance by reporting the Total Error Score (TES) value. Quantification of cone photoreceptor density and integrity by means of Exploring Neural and Optical Mechanisms of Colour Vision through the Farnsworth-Munsell 100 Hue Test.

Material and Method

A cross-sectional comparative study was carried out in the Departments of Physiology and Ophthalmology with 170 medical students to determine the prevalence and pattern of colour vision deficiency (CVD). Ethical approval (IEC No. 976/MC/EC/2019) and written informed consent were obtained before participation. Students aged 18–25 completed a questionnaire on general and ocular health, medication use, refractive correction, colour-related difficulties, and family history of CVD. Colour vision was first screened using Ishihara plates and then assessed in detail with the Farnsworth–Munsell 100 Hue test. Only participants without systemic or ocular disease and not using drugs known to affect colour vision were included.

The Farnsworth–Munsell 100 Hue Test consists of four sets of coloured caps: one set with 22 caps and three sets with 21 caps, each bounded by two fixed anchor caps. Participants arrange the movable caps to create a smooth colour gradient between the anchors. The test is performed under standardised daylight illumination (6500 K) and viewed binocularly without time limits. The timer began when participants indicated readiness and stopped when they confirmed completion. Average completion times for the four sets were 2:58, 2:48, 2:51, and 2:45 minutes, with a total mean time of 11:22 minutes. Results were analysed using FM100 scoring software, providing Total Error Scores (TES), axis-specific errors (Protan, Deutan, Tritan), and box-wise errors for the four hue regions (red–yellow, yellow–green, green–blue, and blue–purple).

Data Collection and Statistical Analysis: Data from the study were analysed using SPSS software, with continuous variables expressed as Mean ± SD and compared using independent t-tests. A p-value < 0.05 was considered statistically significant. Descriptive statistics (Mean, Standard Deviation) were generated for TES and B ox-specific Error Scores (ES).

Results

Table 1: Comparison of Box-specific Error Score (ES) in 170 Medical students' vs Normal Reference Values

Colour Box	Mean Error Score (ES) ±SD Medical students	Normal Reference Mean ± SD	p- Value
Box A	**18.4 ± 6.2**	**10.5 ± 4.0**	**0.042**
Box B	**20.1± 7.5**	**12.0 ± 4.5**	**0.037**
Box C	**22.7 ± 8.1**	**13.2 ± 5.1**	**0.031**
Box D	**19.5 ± 6.8**	**11.4 ± 4.3**	**0.040**
All Boxes TES (A+B+C+D)	**80.7 ± 14.37**	**47.1± 8.99**	**0.028**

The table shows that medical students have higher error scores across all four boxes compared with published norms, indicating mildly reduced hue discrimination. Box C exhibited the greatest errors, consistent with previous findings that this region is most challenging. The p-values (< 0.05) confirm significant differences in error patterns. The Total Error Score (80.7) was also notably higher than expected normal values (47.1), reflecting a general reduction in chromatic sensitivity across the entire colour spectrum rather than a deficit confined to a single axis.

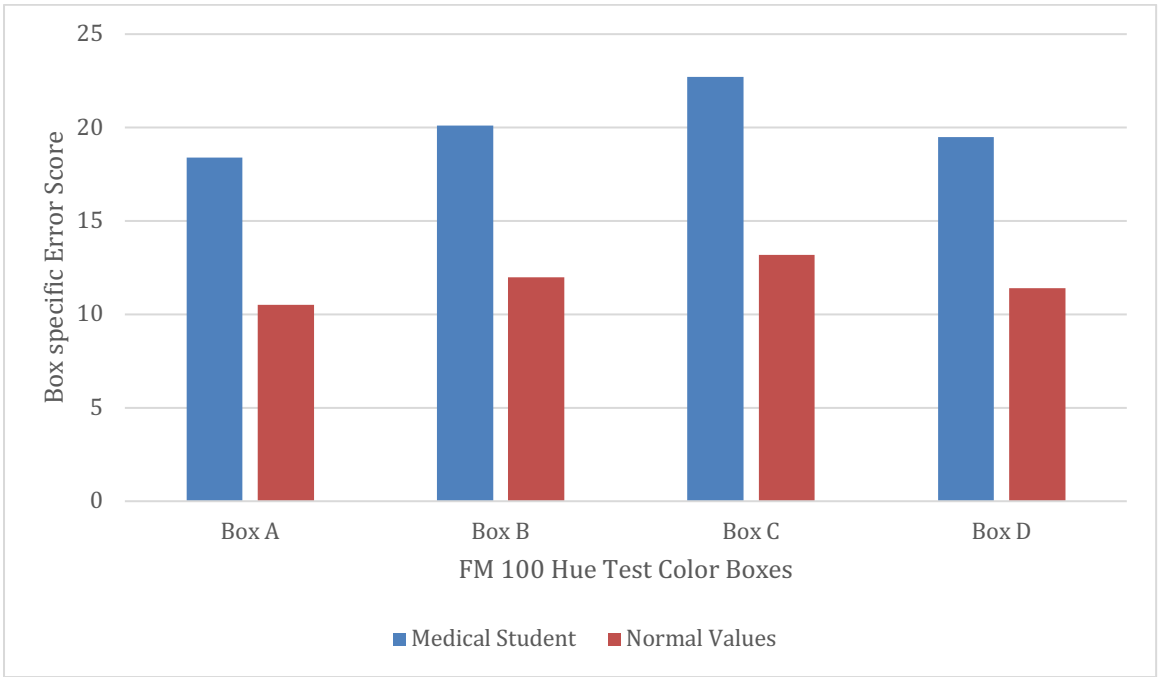

Figure 1: Conclusion Axis Graph: Error Score (ES) of Medical Students vs Normal Reference Values

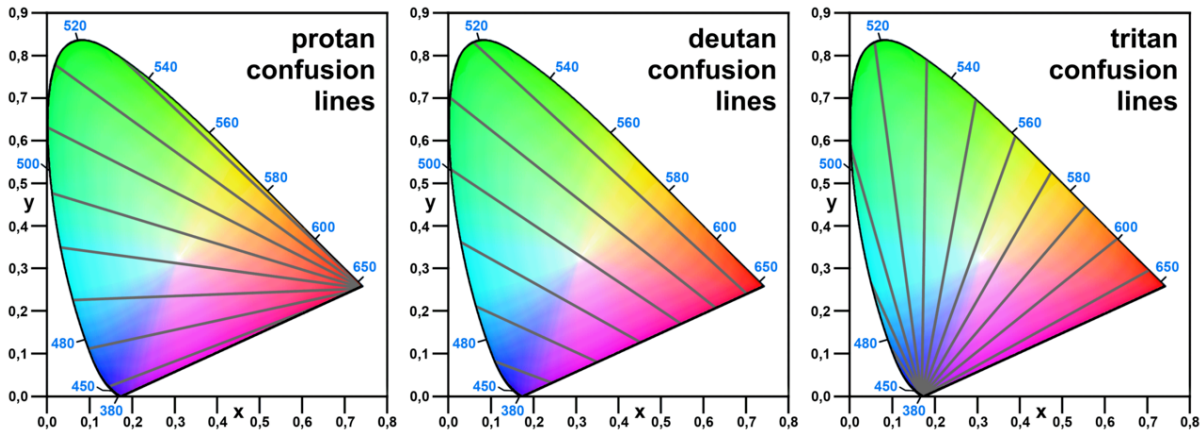

Figure 2: Confusion Axis Circle

Discussion:

This study evaluated colour discrimination in 170 medical students using the Farnsworth–Munsell 100 Hue Test, comparing their Total Error Scores and box-wise errors with normal reference values. The confusion-axis plot showed the greatest deviation along Box C, which corresponds to blue–green to purple–red transitions—commonly the most difficult region due to closely spaced hues. These findings suggest that even individuals with normal colour vision may display mild variations in hue-sorting accuracy, influenced by factors such as lighting, fatigue, attention, or limited familiarity with colour tests.

The Farnsworth–Munsell 100 Hue Test evaluates how well a person can distinguish small differences in colour. During the test, individuals arrange coloured caps in order of hue, and scoring depends on how many caps are misplaced and how far each misplacement is from the correct position. These errors indicate both the presence and the location of any colour-discrimination weakness.

Overview of FM100 Scoring

- **Superior performance:** About 16% of people score a TES between 0 and 16, showing excellent colour-discrimination ability.
- **Average performance:** Most individuals (around 68%) fall between 16 and 100, representing normal chromatic discrimination.
- **Low performance:** A TES above 100, seen in roughly 16% of the population, reflects weaker colour-sorting ability. Retesting may yield small changes, but overall performance remains consistent.

TES ranges, therefore, classify colour-vision ability as Superior (0–16), Average (20–100), or Low (>100). The radial (axis) plot additionally indicates the type and severity of any Protan, Deutan, or Tritan pattern of errors. [9]

De Valois and Webster describe colour vision as the ability to classify and distinguish objects based on differences in the wavelengths they emit or reflect.[10]. Fanlo-Zarazaga et al. (2024) compared the FM-100 with newer automated digital tests and reported that digital systems improve repeatability by reducing variation from examiners and lighting. Their findings suggest that non-standard illumination or manual testing procedures can inflate FM-100 error scores, which may partly explain the higher TES observed in our study.[11]

Age-related reductions in colour discrimination arise from changes in neural processing and in the optical properties of the eye. Although cone numbers remain relatively stable with age, the optical density of cone photopigments can vary, and studies using Rayleigh colour matching suggest that foveal L- and M-cone outer segments may shorten or contain less pigment over time. The S-cone pathway is particularly vulnerable to age-related decline. Ongoing research continues to clarify how chromatic sensitivity develops in early life and changes across the lifespan.[12]

Conclusion

Overall, the results highlight that even young adults without known ocular disease may exhibit subclinical variations in colour discrimination, making routine colour-vision assessment relevant in visually demanding professions.

Clinical and Neurophysiological Implications of the FM 100 Hue Test

1. Sensitive Measure of Chromatic Pathway Integrity

2. Detection of Acquired Colour Vision Deficits

3. Implications for Clinical Competence

4. Indicator of Visual Stress and Neural Adaptation

5. Guiding Vision Care in Healthcare Education

Ethics Statement: The studies involving Medical students were approved by the Institutional Ethics Committee of SMS Medical College, Jaipur, and Rajasthan (Certificate No. 976/MC/EC/2019 dated 27/12 / 2019. Written informed consent from medical students was obtained.

Funding: The author(s) declare that no financial support was received for the research and/or publication of this article

Acknowledgments: The authors gratefully acknowledge the Head of Department of Physiology, SMS Medical College, Jaipur, Rajasthan, India, for permitting the conduct of the FM100 Hue test among students. The authors are very thankful to the Ophthalmology Department for valuable guidance in validating the results.

Generative AI Statement: The authors declare that AI was used in the creation of this manuscript. We have used ChatGPT for writing the Discussion part of the manuscript.

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