



Rods affect S-cone discrimination on the Farnsworth–Munsell 100-hue test

Roger Knight *, Steven L. Buck, Garth A. Fowler, Anh Nguyen

Department of Psychology, Box 351525, University of Washington, Seattle, WA 98195, USA

Received 10 July 1997; received in revised form 30 September 1997

Abstract

Rod influence on hue discrimination was assessed by the Farnsworth–Munsell 100-hue test. Rod influence was taken as the difference in error scores obtained after complete dark adaptation and during the cone plateau at three mesopic (23, 9, 3 td) and one standard (158 td) light level. On the FM 100, rods produced a differential discrimination loss along a tritan axis as compared with a red–green axis without any bias toward a rod confusion axis. Rods appear to impair discrimination mediated by S-cone pathways, which at moderate levels of illumination can differentially elevate tritan errors on the FM 100. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Rod-cone interaction; Farnsworth–Munsell; Chromatic discrimination; S cones; Hue

1. Introduction

Rods produce a variety of important effects on color perception that challenge efforts to build general models of peripheral color vision. At mesopic light levels, rods shift the appearance of hues [1,2], disrupt color matching [3], and reduce wavelength discrimination [4], to illustrate a few of the consequences of rod influence on color vision. The existence of these effects is not surprising because rod signals do not have private pathways from the retina [5], and therefore, at some stage or stages of retinal processing the visual system must simultaneously deal with both rod and cone signals.

Rod influence on color vision suggests that rod signals affect chromatic pathways. The purpose of this study is to assess rod influence on chromatic pathways using a test of hue discrimination. The Farnsworth–Munsell 100-hue test (FM 100) reliably distinguishes between two important axes in color space: (1) a red–green axis involving changes in L- and M-cone excitation, and (2) a tritan axis involving changes in S-cone excitation [6]. These axes represent two spectral mechanisms thought to reflect important retinal substrates for

color vision: midget cells and small-bistratified ganglion cells [7]. If rods interact with chromatic pathways early in the visual process then rods should affect discrimination along one or both color axes. Nagy and Doyal [8] found rods to reduce red–green discrimination in peripheral vision but did not investigate tritan discrimination. We find that rods impair tritan discrimination on the FM 100 suggesting rod involvement with S-cone pathways.

2. Methods

2.1. Observers

Five color-normal, experienced observers (age 24–42 years) participated in all conditions. Judgments were made monocularly with the right eye.

2.2. Stimuli and procedures

Spectral calibrations of all FM 100 caps, neutral density filters (Wratten no. 96), and illuminant (MacBeth Easel lamp, CCT 6663 K) were performed with a PhotoResearch PR-650 SpectraScan photometer. From these measurements the S-, M-, and L-cone and rod troland values of each cap under each condition were

* Corresponding author. Fax: +1 206 6053157; e-mail: Rknight@u.washington.edu.

calculated. Cone troland values were calculated from the Smith and Pokorny cone fundamentals [9], following the methods of Boynton and Kambe [10] and Smith et al. [6]. The photopic luminance value of each cap was converted to effective trolands using Le Grand's [11] estimates of pupil area corrected for the Stiles–Crawford effect. Rod excitation was calculated using V'_λ [12] and converted to rod trolands using the transformation from ref. [13].

Fig. 1 shows the variation of cone and rod excitation for our set of FM 100 caps at the 23 td light level used in our experiment. Fig. 1(a) shows the variation of S-cone excitation (solid circle) and L-cone excitation (open circles) with cap number. Solid arrows indicate cap regions of minimal change of excitation values for S-cones which identifies the red–green confusion loci. Dashed arrows indicate cap regions of minimal change of excitation values for L-cones (and M-cones, since $L + M$ is constant) which identifies the tritan confusion loci. Caps that fell at or near the confusion loci were selected to represent caps belonging to a given confusion axis. By this criterion, caps 13–18 and 53–66 constitute the red–green confusion axis, and caps 85–6 and 43–52 constitute the tritan confusion axis.

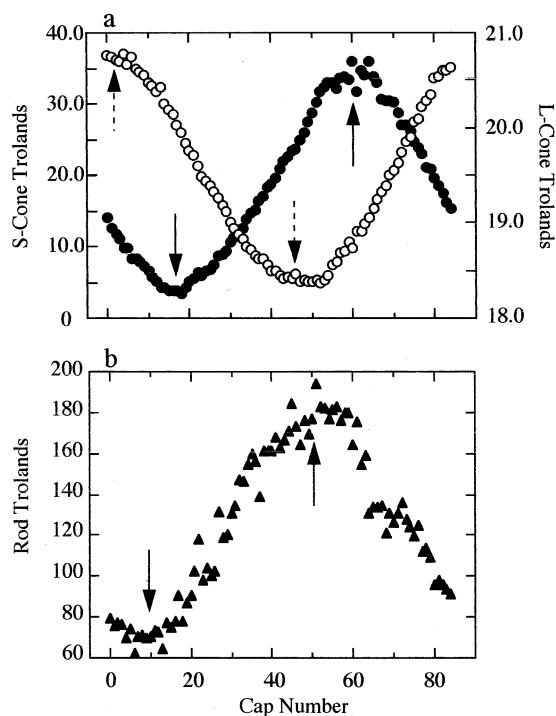


Fig. 1. Cone and rod excitation of the FM 100 as a function of cap number for a light level of 23 td. Panel (a) shows S-cone (solid circle) and L-cone (open circle) excitation in cone troland units. The solid arrows point to the red–green confusion axis and the dashed arrows point to the tritan axis. Panel (b) shows rod (solid triangle) excitation with solid arrows pointing to the rod confusion axis. The variation of cone and rod excitation with cap number and the location of the confusion axes are the same for all light levels.

Fig. 1(b) shows the variation of rod excitation (solid triangle) within the FM 100 set. The solid arrows indicate the points of minimal change of rod excitation values with caps 5–11 and 50–59 representing the rod confusion axis. The locations of the rod and cone confusion axes did not vary with light level, but the absolute troland values shown at the (23 td) light level were scaled proportionally at other light levels.

Observers viewed the FM 100 caps at four light levels (158, 23, 9 and 3 td) using the traditional four box set that provides a black viewing surface for cap arrangement. Observers either dark-adapted for 30 min prior to testing or viewed a ganzfeld bleaching stimulus produced by a strong tungsten-halogen projector lamp light for 60 s followed by a 3 min waiting period before testing on the cone plateau for 3–5 min. For each light level, observers attached the appropriate neutral density filters to a filter holder mounted in front of the right eye. Observers completed only one box of caps after each bleach, thus, four bleaching cycles were required to complete a single cone-plateau condition. The time to arrange the caps in a single box did not differ between dark-adapted and cone-plateau conditions. The test was repeated twice for each condition with the order of conditions counter-balanced across days to avoid practice effects [14].

The Kinnear method [15] was used to calculate error scores.

3. Results

Fig. 2 shows error scores for FM 100 hue discrimination at four light levels for both dark-adapted (solid circle) and cone-plateau (open circle) conditions. For each cap the error score is the mean of the five observers' individual means. At 158 td, there are few errors in either condition but in the dark-adapted condition there is a very small, but significant increase in error scores for tritan caps 43–52. Lowering light level results in some increase of errors for all caps, but, as expected [16], a characteristic pattern of tritan loss develops under both conditions. Rods augment the development of a tritan axis by differentially increasing error scores along the tritan axis in the dark-adapted condition compared with the cone-plateau condition. This rod effect is clearly present at 23 td where dark-adapted error scores are elevated at both poles of the tritan axis (caps 85–6 and 43–52) compared with the cone-plateau condition. At even lower light levels, 9 and 3 td, there is a continued difference in tritan error scores in the dark-adapted versus the cone-plateau condition. The size of the rod influence diminishes for caps 85–6 at the lowest light levels but a substantial effect is present for caps 43–52. This difference may be related to a ceiling effect for discrimination errors

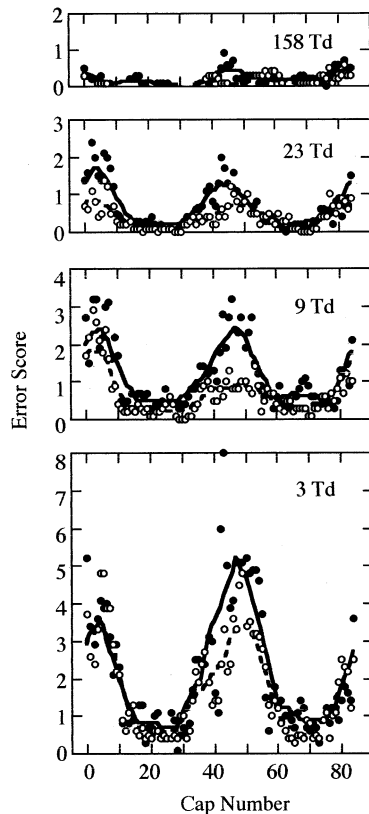


Fig. 2. FM 100 error scores for dark-adapted (solid circle) and cone-plateau (open circle) conditions at four light levels: 158 td (630 scot. td); 23 td (61 scot td); 9 td (26 scot td); 3 td (9 scot td). Error scores are the mean of the five observers' individual means. The solid and dashed lines are smoothing functions fit to the dark-adapted and cone-plateau data, respectively.

resulting from the low levels of S-cone excitation in caps 85–6 at these light levels.

Table 1 shows the effect of rods on error scores for regions of the FM 100 belonging to each pole of the red–green and tritan axes. Individual cap error scores are summed across the caps selected to represent each axis pole. A measure of rod influence is obtained by subtracting the cone-plateau from the dark-adapted error scores. Error scores tend to be elevated by rods for both poles of the red–green and tritan axes. The only exception is for the red–green axis, caps 53–66, at 23 and 158 td, where the error score is slightly higher for the cone-plateau condition. It is difficult to compare error scores between two poles of the same confusion axis because the number of caps are not identical.

A smoothing function was fit to the dark-adapted (solid line) and cone-plateau (dashed line) data of Fig. 2 to reduce the noisiness of the data and make clear the extent of rod influence. For each cap number, the smoothing function takes the average error score of the cap and of the five adjacent caps on each side to calculate a running average of 11 caps. Errors due to rod influence tend to accumulate symmetrically around

each pole of the tritan axis without any evidence for errors accumulating along a rod axis located between caps 50 and 57 [17]. In fact, the only condition that differs noticeably from the common tritan axis is the cone-plateau condition for 23 td, a condition to which rods presumably do not contribute.

A discrete Fourier analysis was used to further evaluate whether rods produce a shift in the confusion axis in the direction of a rod axis. For the three lowest light levels, Fourier analysis reveals a large two-cycle frequency component for all conditions in addition to a dc component. At 9 td, a one-cycle component is also present in the cone-plateau condition that is not present in the other conditions. A two-cycle cosine wave is fitted to the data in order to assign a cap number, or center-cap, to the loci of the confusion axis. Table 1 shows the center-cap values for each condition. There is no significant nor systematic shift in the center cap of the tritan confusion axis between dark-adapted and cone-plateau conditions, and there is no systematic shift in the tritan axis as a simple function of light level for the dark-adapted condition. There appears to be a small, systematic shift, for the cone-plateau condition.

4. Discussion

Under dark-adapted conditions, rod influence produces a relatively large, light-level-dependent increase of errors on the FM 100 along a tritan confusion axis, with only small increases along other axes. This rod-induced loss of S-cone-mediated chromatic discrimination grows as light level drops below that of the standard viewing conditions for the FM 100 and is most pronounced at 9 td, in our data. This rod-induced chromatic-discrimination loss augments a separate, purely cone-based S-cone chromatic discrimination loss that has been previously documented [18,16,19].

We conclude that the present results show a direct effect of rod signals on S-cone mediated chromatic discrimination, and that we can eliminate two alternative, indirect explanations. First, scotopic brightness cues might, in some sense, compete with weak S-cone-mediated hue signals and mislead observers into ordering the caps incorrectly. This predicts that, as light level is reduced, there should be an accumulation of errors in the vicinity of the rod axis resulting in an apparent shift of the observed confusion axis away from the tritan axis and toward the rod axis. However, we do not find any evidence for such a shift for any of the light levels we tested.

Second, given the light-level dependence of purely cone-mediated tritan errors on the FM 100, differences of pupil size between corresponding dark-adapted and cone-plateau conditions could result in differences in the number of tritan errors between those conditions,

Table 1
Effect of rod influence [dark adaption (DA) minus cone-plateau (CP)] on red–green and tritan discrimination errors and position of tritan confusion axis

Light level	Tritan axis										Red–green axis											
	Error scores					Position (Cap no.)					Error scores					Position (Cap no.)						
	Caps 85–86					Caps 43–52					Caps 13–18					Caps 53–66						
	DA (SE)	CP (SE)	DA-CP	DA (SE)	CP (SE)	DA-CP	DA (SE)	CP (SE)	DA-CP	DA (SE)	CP (SE)	DA-CP	DA (SE)	CP (SE)	DA-CP	DA (SE)	CP (SE)	DA-CP	DA (SE)	CP (SE)	DA-CP	
158 td	1.5 (0.6)	0.6 (0.4)	0.9	4.0 (1.7)	0.3 (0.3)	3.7	—	—	—	2.3 (1.5)	0.0 (0.0)	2.3	2.7 (0.4)	0.0 (0.0)	2.3	2.8 (1.0)	2.8 (1.0)	—	2.7 (0.4)	2.8 (1.0)	—	—0.1
23 td	12.5 (3.5)	5.5 (2.4)	7.0	11.8 (3.2)	7.8 (3.7)	4	45 (1.0)	45 (1.4)	0	1.6 (0.8)	0.8 (0.6)	0.8	4.2 (1.5)	0.8 (0.6)	0.8	4.9 (1.9)	4.9 (1.9)	0	4.2 (1.5)	4.9 (1.9)	0	—0.7
9 td	17.9 (4.3)	15.6 (4.7)	2.3	24.6 (6.6)	8.8 (3.3)	15.8	47 (1.2)	46 (1.6)	1	3.8 (2.0)	1.6 (0.8)	2.2	10.3 (3.8)	1.6 (0.8)	2.2	7.8 (3.0)	7.8 (3.0)	1	10.3 (3.8)	7.8 (3.0)	1	2.5
3 td	27.1 (4.1)	25.5 (4.0)	1.6	51.2 (9.9)	34.2 (8.2)	17	46 (1.1)	47 (1.0)	—1	5.2 (2.1)	4.6 (2.9)	0.6	27.4 (10.1)	4.6 (2.9)	0.6	19.8 (6.1)	19.8 (6.1)	—1	27.4 (10.1)	19.8 (6.1)	—1	7.6

without any rod influence. This would be a concern if pupil diameters were larger in the cone-plateau conditions (producing higher retinal illumination and fewer cone-mediated tritan errors) than in the dark-adapted conditions. However, the evidence we have demonstrates just the opposite, that pupil diameters were actually smaller in the cone-plateau conditions. We measured pupil diameter by a visual matching technique [20] for two observers and found that pupil area was on average 18% smaller in the 123 td. cone-plateau condition than in the corresponding dark-adapted condition. We could not make pupil-size measurements at the lower light levels, but since pupil diameter is importantly controlled by the adaptive state of the eye, the discrepancies between dark-adapted and cone-plateau might be expected to increase as light level drops. This prediction follows from the supposition that the constant-illuminance bleaching light would tend to minimize pupil-size variation among the cone-plateau conditions, whereas under dark-adapted conditions the progressively lower stimulus light levels would tend to produce progressively larger pupils.

Taken together with Nagy and Doyal's demonstration of rod impairment of threshold-level red–green discrimination [8], the present results suggest two conclusions. First, a rod effect may disrupt near-threshold red–green discrimination but not significantly affect suprathreshold red–green discrimination on the FM 100. Second, the rod influence on both tritan and red–green discrimination is one of impairment of chromatic discrimination in color-normal observers. In contrast, there are circumstances under which rod involvement appears to improve chromatic discrimination for color-deficient observers [21,22]. The basis for these differences remain to be determined.

Acknowledgements

Supported by NIH grant EY03221 awarded to SLB. We thank David Baldwin for his assistance with the Fourier analysis.

References

[1] Buck S, Knight R, Fowler G, Hunt B. Rod influence on hue-scaling functions. *Vis Res* 1998;38:3259–63.

- [2] Lythgoe R. Dark-adaptation and the peripheral colour sensations of normal subjects. *Br J Ophthalmol* 1931;15:193–210.
- [3] Trezona P. Rod participation in the 'blue' mechanism and its effect on colour matching. *Vis Res* 1970;10:317–32.
- [4] Stabell S, Stabell U. Wavelength discrimination of peripheral cones and its change with rod intrusion. *Vis Res* 1977;17:423–6.
- [5] Daw NW, Jensen RJ, Brunken WJ. Rod pathways in mammalian retinae. *Trends Neurosci* 1990;3:110–5.
- [6] Smith VC, Pokorny J, Yeh T. The Farnsworth–Munsell 100-hue test in cone excitation space. In: Drum B, editor. *Color Vision Deficiencies XI: Documenta Ophthalmologica Proceedings Series*, 1993:281–91.
- [7] Dacey DM, Lee BB. The blue-ON opponent pathway in primate retina originates from a distinct bistratified ganglion cell type. *Nature* 1994;367:731–5.
- [8] Nagy AL, Doyal JA. Red–green color discrimination as a function of stimulus field size in peripheral vision. *J Opt Soc Am* 1993;10:1147–56.
- [9] Smith VC, Pokorny J. Spectral sensitivity of the foveal cone photopigments. *Vis Res* 1975;12:2059–71.
- [10] Boynton RM, Kambe N. Chromatic differences steps of moderate size measured along theoretically critical axes. *Colour Res Appl* 1980;5:13–23.
- [11] Le Grand Y. *Light, Colour and Vision*. New York: Wiley, 1957.
- [12] Wyszecki G, Stiles WS. *Color Science: Concepts and Methods, Quantitative Data and Formulae* 2nd Ed. New York: Wiley, 1982.
- [13] Shapiro AG, Pokorny J, Smith VC. Cone-rod receptor spaces with illustrations that use CRT phosphor and light-emitting-diode spectra. *J Opt Soc Am* 1996;12:2319–28.
- [14] Hardy KJ, Craven B, Foster DH, Scarpello JHB. Extent and duration of practice effects on performance with the Farnsworth–Munsell 100-hue test. *Ophthalmic Physiol Opt* 1994;14:306–9.
- [15] Kinnear PR. Proposals for scoring and assessing the 100-hue test. *Vis Res* 1970;10:423–33.
- [16] Smith VC, van Everdingen JAM, Pokorny J. Sensitivity of arrangement tests as evaluated in normals at reduced levels of illumination. In: Drum B, Moreland JD, Serra A, editors. *Colour Vision deficiencies X, Documenta Ophthalmologica Proceedings Series*, 1991:177–85.
- [17] Pokorny J, Smith VC, Verriest G, Pinckers A. *Congenital and Acquired Color Vision Defects*. New York: Grune and Stratton, 1979.
- [18] Knoblauch K, Saunders F, Kusuda M, Hynes R, Podgor M, Higgins KE, de Monasterio FM. Age and illuminance effects in the Farnsworth–Munsell 100-hue test. *Appl Opt* 1987;26:1441–8.
- [19] Yeh T, Pokorny J, Smith VC. S-cone discrimination sensitivity and performance on arrangement tests. In: Drum B, editor. *Color vision deficiencies XI, Documenta Ophthalmologica Proceedings Series*, 1993:293–302.
- [20] Pokorny J, Smith VC. How much light reaches the retina? In: Cavonius CR, editor. *Colour Vision Deficiencies XIII, Documenta Ophthalmologica Proceedings Series*, 1997:491–511.
- [21] Reitner A, Lindsay TS, Zrenner E. Is colour vision possible with only rods and blue-sensitive cones? *Nature* 1991;352:798–800.
- [22] Paramei GV, Bimler DL, Cavonius CR. Effects of luminance on the color perception of protanopes. *Vis Res* 1998;38:3397–401.