ELSEVIER

Measuring Short-Wavelength–Sensitive Cone Discrimination Thresholds Using Pseudoisochromatic Figures Displayed on a Color Monitor

Akira Watanabe, Joel Pokorny and Vivianne C. Smith

Visual Sciences Center, The University of Chicago, Chicago, IL, USA

Purpose: To simplify the testing of short-wavelength–sensitive (SWS) cone function in the clinic.

Methods: SWS-cone discrimination thresholds were measured along the tritan axis using pseudoisochromatic figures displayed on a color monitor. A circular 6° field, containing spatially discrete patches of varying sizes and luminances, was presented on a background. A subset of patches formed the target patch in the shape of a C. Eight subjects with normal color vision reported the direction of the gap in the C using a cursor controlled by a joystick. Data were expressed in units of SWS-cone trolands.

Results: SWS-cone discrimination threshold increased slowly as the SWS-cone trolands of the starting chromaticity increased. The dependence of the threshold on the SWS-cone activation level was similar to literature reports of chromatic discrimination measured with conventional paradigms.

Conclusions: The advantages of this method: (a) It is a simple intuitive task for patients. (b) The paradigm can be implemented with an 8-bit/gun color monitor. (c) The test avoids the need to define equiluminance for the individual patient before the color test is administered. This method can provide a useful technique for measuring SWS-cone function in a clinical population. **Jpn J Ophthalmol 1999;43:5–8** © 1999 Japanese Ophthalmological Society

Key Words: Pseudoisochromatic figures, SWS-cone discrimination thresholds.

Introduction

Two patches of light can be discriminated on the basis of a difference in luminance or chromaticity. Here we are concerned with chromatic discriminations based upon differences in the activation of the short-wavelength–sensitive (SWS) cone system. Generally, the SWS-cone discrimination threshold increases as SWS-cone activation is increased. If the discrimination thresholds are measured along an equiluminant plane in which the long-wavelength–sensitive (LWS) and middle-wavelength–sensitive (MWS) cone stimulation is kept constant (a tritan line), the results may be expressed as a difference in the SWS-cone trolands relative to the SWS-cone trolands at the starting chromaticity. Boynton and Kambe,[1] Yeh et al[2] and Miyahara et al[3] showed SWS-cone threshold-vs-retinal illuminance (TVR) functions using this paradigm. The TVR functions did not differ with changes in the proportions of LWS- and MWS-cone activation; that is, SWS-cone discrimination can be measured along any one of a number of tritan lines.

Short-wavelength–sensitive cone pathways are said to be more vulnerable to disease than other cone pathways[4,5] and, thus, may be important both in theoretical color vision research and in clinical applications. A preferential loss of SWS-cone pathway sensitivity has also been demonstrated in patients with diabetes.[6] Sandberg and Berson[7] found a larger loss of $\pi-1$ (SWS-cone pathway) than $\pi-4$ (MWS-cone pathway) in retinitis pigmentosa using psychophysical testing. Previous psychophysical methods of

Received: February 5, 1998

Correspondence and reprint requests to: Akira WATANABE, MD, Department of Ophthalmology, Jikei University School of Medicine, 3-25-8 Nishi-Shinbashi, Minatoku, Tokyo, 105-8461 Japan

Jpn J Ophthalmol 43, 5–8 (1999)

Published by Elsevier Science Inc.
0021-5155/99/$–see front matter
PII S0021-5155(98)00054-9

Jpn J Ophthalmol
Vol 43: 5–8, 1999

assessing SWS-cone sensitivity in patient populations have proved difficult, especially for elderly or handicapped patients. Here we describe an inexpensive method to measure SWS-cone thresholds that is a simple intuitive task for patients.

Pseudoisochromatic (PIC) plates have been used for over a century to diagnose color vision defects. These plates typically employ figures and backgrounds constructed of spatially discrete patches of varying size and luminance. The design features avoid the need to define equiluminance for an individual subject because the luminance noise and masking contours ensure that the subject's responses depend on chromatic rather than luminance signals.

Regan et al[8] developed a computer-controlled PIC test for red/green color vision. Their test achieved a good separation of protan and deutan subjects and revealed a large range of chromatic sensitivities among the anomalous trichromats. We used their method for the stimuli and developed a simple chromatic discrimination test for stimuli that varied in the SWS-cone test.

Subjects and Methods

Eight subjects, ranging in age from 25–30 years, participated in these experiments. Each subject was examined with the Nagel anomaloscope and Standard Pseudoisochromatic Plates Part 2 (SPP) part II, and all were judged to have normal color vision. Written informed consent was obtained from all subjects.

C-shaped PIC targets[8] were generated using a Macintosh IICi computer and displayed on a Sony GDM-17SE1 color monitor. The resolution of the monitor was 640 × 480. The number of colors that could be displayed simultaneously on the monitor was 256. The computer specified the output of each gun of the monitor with an 8-bit/gun resolution. A circular 6° field containing spatially discrete patches of varying size and luminance was presented on a 14.0° × 10.4° background (Figure 1). The background luminance was 5 cd/m^2, which was slightly dimmer than the lowest luminance dots. The chromaticity of background was the same as the chromaticity of the field patches. A subset of patches formed the target in the shape of a C. The outer diameter of the C subtended 4.3°, the inner diameter 2.2°, and the gap 1°. For both the field and the target patches, the luminance of any patch was randomly assigned on each trial to one of six equally spaced and equally probable levels in the range 7.6–17.0 cd/m^2.

The luminance of the patches varied from trial to trial. The stimulus spatial pattern was kept the same during one session. The orientation of the target C was randomly changed from trial to trial. The gap was located at one of four positions: left, up, right, and down. The chromaticity of the target patches was varied from the starting chromaticity in incremental and decremental directions along the tritan line. On the tritan line the level of SWS-cone activation was varied for constant LWS- and MWS-cone activation. The examiner chose 12 starting chroma-

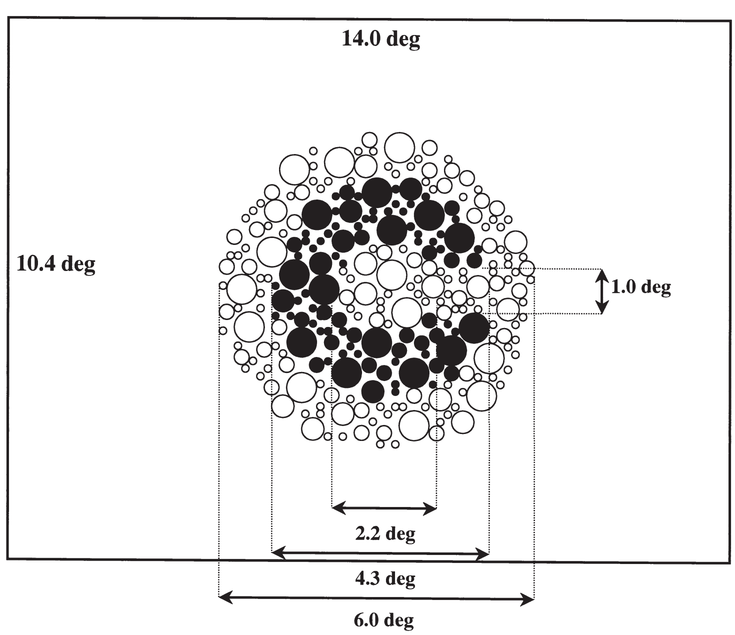

Figure 1. Spatial characteristics of C-shaped pseudoisochromatic (PIC) targets developed in this study. Composition is based on the targets of Regan, Reffin and Mollon,[8] with changes in the background chromaticity and starting chromaticities.

ticities on the tritan line. At the most bluish and yellowish starting chromaticity, he could measure the chromatic discrimination threshold in only one direction because of the limitations of the monitor.

The subject viewed the color monitor from a distance of 112 cm. The stimuli were presented on the color monitor for 5 seconds. The subject reported the direction of the gap in the target C with a cursor using a joystick. If the subject did not respond within 5 seconds, the stimulus disappeared and the program continued to the next trial. The computer treated nonresponses as incorrect responses.

Short-wavelength–sensitive-cone chromatic discrimination thresholds were measured along the tritan axis using a 2-down-1-up double staircase procedure. Testing on any one staircase was terminated after nine reversals. The average of the last four reversals was taken to compute chromatic discrimination thresholds. It required about 50 minutes to measure the SWS-cone chromatic discrimination threshold on one axis for 12 starting chromaticities.

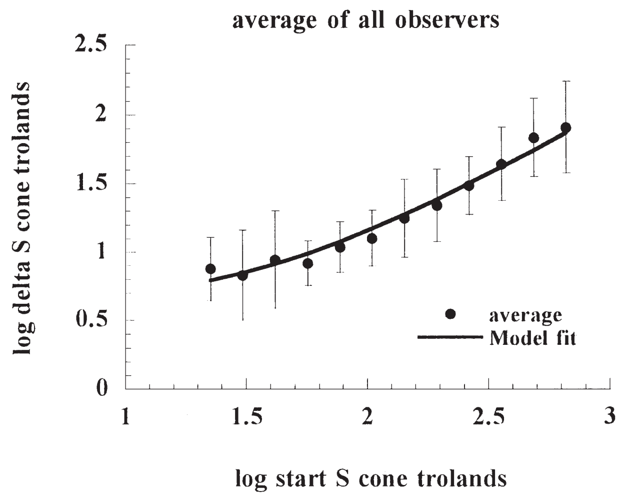

Figure 2. Threshold-vs-retinal illuminance (TVR) functions, average of 8 subjects. Log delta short-wavelength–sensitive (SWS) cone trolands are plotted vs log SWS-cone trolands at starting chromaticity. Line fits Equation (1). Error bars represents plus and minus 2 SD for each starting chromaticity.

Results

The average discrimination thresholds for the 8 subjects are shown in Figure 2. The horizontal axis is the logarithm of SWS-cone trolands at a starting chromaticity, and the vertical axis is the logarithm of SWS-cone trolands discrimination threshold. The error bars represent 2 SD for each starting chromaticity. For all subjects, chromatic discrimination thresholds increased slowly as the starting chromaticity increased and approached the Weber region at a high SWS-cone troland level.

Boynton and Kambe[1] suggested a gain equation, $\Delta B = Co\,(B + kBo)$, where Co is the limiting Weber fraction, Bo is the SWS-cone dark noise, and k is an individual sensitivity parameter. In their experiment, all data were well-fitted by a single function. Boynton and Kambe's equation was rewritten by Miyahara et al:[3]

$$\Delta S = S\,thr[1 + S(SR)] \qquad (1),$$

where S thr is the absolute SWS-cone threshold and SR is the reciprocal SWS-cone trolands at which threshold is raised twofold. We fitted our data to this equation, and estimated the parameters using a least-squares minimization procedure. For the averaged data, S thr was 3.81 and SR was 0.027. The limiting Weber fraction was about 11% in our study, and the individual variance for SWS-cone absolute discrimination threshold spanned about 0.6 log units.

Discussion

Color normal subjects may show large variations in their luminance matches during testing. Usually the technique of heterochromatic flicker photometry (HFP) has been used to determine personal luminance matches, the so-called sensation luminance,[9] for each subject for the various field configurations. Such a procedure is time-consuming because of the time required for the actual measurement, and the time required to familiarize the subject with the photometric procedure. To avoid the need to define equiluminance for the individual subject, Regan et al[8] suggested that the presence of luminance noise and masking contours in PIC stimuli could ensure that the subject's responses depended on chromatic signals. They included spatial and luminance noise in the stimulus by forming the target and field from a mosaic of discrete patches that each had its own contour and varied randomly in luminance. Thus neither edge artifacts nor luminance differences could be used as cues for the discrimination of the target against the field. We extended their paradigm and developed a simple chromatic discrimination sensitivity test that included changes in the background chromaticity and starting chromaticities.

Figure 3 shows a comparison of data from this study and other chromatic discrimination data[1–3] obtained at a similar retinal illuminance level (110–120 trolands), but with dark surrounds. SWS-cone chro-

Jpn J Ophthalmol
Vol 43: 5–8, 1999

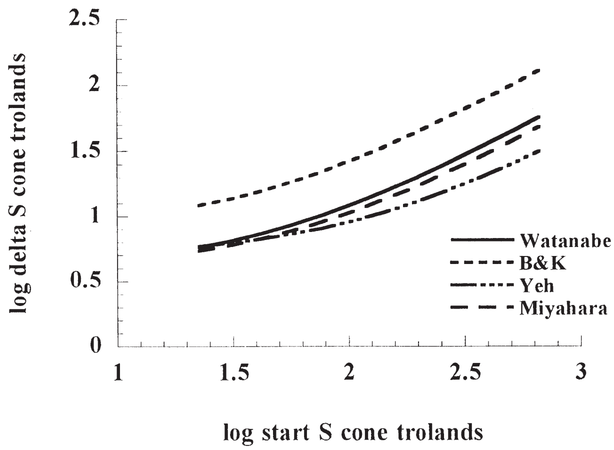

Figure 3. Comparison of data from this study and chromatic discrimination data of Boynton and Kambe,[1] Yeh et al,[2] and Miyahara et al.[3] Threshold-vs-retinal illuminance functions for all four studies are expressed as log delta short-wavelength–sensitive (SWS) cone trolands vs log SWS-cone trolands.

matic discrimination thresholds increased slowly with increases in the SWS-cone activation and approached the Weber region only at high levels of SWS-cone stimulation. Boynton and Kambe[1] (B&K) employed a method for measuring chromatic discrimination in which the subject had to indicate correctly the direction of a chromatic change as well as the fact that two stimulus fields differed in appearance. This method resulted in substantially larger discrimination steps than more conventional discrimination paradigms where threshold is defined as correctly noting the presence of a chromatic difference but not the chromatic direction.[2,3] The data of Boynton and Kambe[1] are parallel but are less sensitive than the data of Yeh et al[2] (Yeh) and Miyahara et al (Miyahara).[3] Our data show thresholds similar to the data of Yeh et al[2] and Miyahara et al[3] at low SWS-cone activation, but a slightly steeper slope. This result probably reflects our use of a surround matched in chromaticity to the starting chromaticity.

Miyahara et al[3] reported that the luminance and chromaticity of the background affected chromatic discrimination thresholds. For an equiluminant white or yellow surround, the chromatic discrimination threshold showed a minimum at the level of SWS-cone activation of the surround, giving a V-shape for the white surround and a monotonic increasing function for the yellow surround. These V-shapes are characteristic of second site opponent effects.[1,3] For a dimmer white surround, the minimum remained at the white point but the V-shape shallowed. Boynton and Kambe[1] and Miyahara et al[3] noted that with a dark surround, some subjects showed a minimum at the starting chromaticity of equal energy white, whereas others showed a monotonic TVR function.

In our study, the surround was matched to the starting chromaticity and, therefore, we expected to assess the first site cone-pathway specific effects primarily and thus a monotonic function that would be fit by Equation (1).

In another study,[10] we measured discrimination for changes in the proportion of LWS- and MWS-cone activation at a constant level of SWS-cone activation and found discrimination to be poorer for PIC stimuli than for spatially homogeneous stimuli.

This work was supported in part by NEI grants EY00901 and EY07390, and an RPB Foreign Research Fellowship to AW. The authors thank John Mollon for providing design details for the C-shaped pseudoisochromatic targets.

References

1. Boynton RM, Kambe N. Chromatic difference steps of moderate size measured along theoretically critical axes. Color Res Appl 1980;5:13–23.
2. Yeh T, Pokorny J, Smith VC. Chromatic discrimination with variation in chromaticity and luminance: Data and theory. Vision Res 1993;13:1835–45.
3. Miyahara E, Smith VC, Pokorny J. How surrounds affect chromaticity discrimination. J Opt Soc Am 1993;10:545–53.
4. Mollon JD. A taxonomy of tritanopias. Doc Ophthalmol Proc Ser 1982;33:87.
5. Zrenner E. Electrophysiological characteristics of the blue sensitive mechanism: Test of a model of cone interaction under physiological and pathological condition. Doc Ophthalmol Proc Ser 1982;33:103.
6. Zwas F, Weiss H, McKinnon P. Spectral sensitivity measurements in early diabetic retinopathy. Ophthalmic Res 1980; 12:87–96.
7. Sandberg MA, Berson EH. Blue and green cone mechanisms in retinitis pigmentosa. Invest Ophthalmol Vis Sci 1977;16: 149–57.
8. Regan BC, Reffin JP, Mollon JD. Luminance noise and the rapid determination of discrimination ellipses in colour deficiency. Vision Res 1994;34:1279–99.
9. Kaiser PK. Sensation luminance: a new name to distinguish CIE luminance from luminance dependent on an individual's spectral sensitivity. Vision Res 1988;28:455–6.
10. Watanabe A, Pokorny J, Smith VC. Red-green chromatic discrimination with variegated and homogeneous stimuli. Vision Res. In Press.