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Computerized Color Vision Test Based Upon Postreceptoral Channel Sensitivities

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Abstract

An automated, computerized color vision test was designed to diagnose congenital red-green color vision defects. The observer viewed a yellow appearing CRT screen. The principle was to measure increment thresholds for three different chromaticities, the background yellow, a red, and a green chromaticity. Spatial and temporal parameters were chosen to favor parvocellular pathway mediation of thresholds. Thresholds for the three test stimuli were estimated by 4AFC, randomly interleaved staircases. Four 1.5°, 4.2 cd/m² square pedestals were arranged as a 2 x 2 matrix around the center of the display with 15° separations. A trial incremented all four squares by 1.0 cd/m² for 133 msec. One randomly chosen square included an extra increment of a test chromaticity. The observer identified the different appearing square using the cursor. Administration time was ~5 minutes. Normal trichromats showed clear Sloan notch as defined by log ($\Delta Y/\Delta R$), whereas red-green color defectives generally showed little or no Sloan notch, indicating that their thresholds were mediated by their luminance system, not by the chromatic system. Data from 107 normal trichromats showed a mean Sloan notch of 0.654 (SD = 0.123). Among 16 color vision defectives tested (2 protanopes, 1 protanomal, 6 deuteranopes, 7 deuteranomals), the Sloan notch was between -0.062 and 0.353 for deuterans and was < -0.10 for protans. A sufficient number of color defective observers have not yet been tested to determine whether the test can reliably discriminate between protans and deuterans. Nevertheless, the current data show that the test can work as a quick diagnostic procedure (functional trichromatism or dichromatism) of red-green color vision defect.

Keywords

Color vision test; color vision deficiencies; psychophysics

Introduction

Red-green congenital color vision defects are common forms of color vision defects. Their incidences are approximately 8% among Caucasian males (Pokorny, Smith, Verriest and Pinckers 1979; Sharpe, Stockman, Jägle and Nathans 1999). Despite rather high incidences of the red-green color vision defects, currently available screening procedures require special equipment such as pseudoisochromatic plates and a special test illuminant. Precise diagnosis requires an anomaloscope. It would be convenient if we could screen and even eventually diagnose red-green color vision defects with common office equipment, such as a personal computer (PC). The purpose of this study was to develop such a diagnostic computerized test in a laboratory setting with a potential for devising a test for generic PC's in the future.

The red-green color vision defects involve the alteration or lack of the L- or M-cone photopigments. As a consequence the signal strength in the spectral opponent channel of the parvocellular pathway (Derrington, Krauskopf and Lennie 1984) is reduced. Studies that revealed parvocellular pathway activity used increment thresholds on bright white backgrounds (Sperling and Harwerth 1971; Foster and Snelgar 1983). The bright backgrounds provided adaptation of the magnocellular pathway. Normal trichromats showed a Sloan notch, a pronounced decrement in spectral sensitivity at the background chromaticity and enhanced sensitivity for middle-and long-wavelength light (Sloan 1928). Miyahara, Pokorny and Smith (1996) demonstrated that the Sloan notch does not occur in dichromats and is very shallow or absent in anomalous trichromats due to the reduced chromatic sensitivity in the parvocellular pathway. A computer test with a conventional CRT monitor cannot provide bright white backgrounds. An alternate method is needed to decrease sensitivity or suppress the magnocellular pathway. In a pilot study, Hsu, Pokorny and Smith (2000) developed an increment threshold color vision test for the CRT monitor using a 1 sec raised cosine test stimulus (a relatively ineffective stimulus for the magnocellular pathway) and successfully classified protans and deutans.

In this study we adopted a different strategy. Recent investigation of psychophysical paradigms to segregate the parvocellular and the magnocellular pathway responses suggested that the use of the pedestal- Δ -pedestal paradigm could suppress the magnocellular pathway sensitivity thus favoring detection by the parvocellular pathway (Pokorny and Smith 1997; Smith, Pokorny and Sun 2000; Smith and Pokorny 2003).

We expect that normal trichromats will have enhanced sensitivity at the green and red stimuli and decreased sensitivity at the yellow stimulus. In comparison, dichromats should make thresholds consistent with their luminosity functions. In this pedestal- Δ -pedestal paradigm, four stationary luminance pedestals were presented at all times with the surround. At the onset of a trial, a further spatiotemporal luminance increment of the pedestal, the Δ pedestal, occurred for all the pedestals. One of the pedestals, a randomly designated test stimulus, contained an additional increment (luminance and/or chromatic) above the Δ pedestal. The observer was asked to choose the one stimulus that was different from the other three. In the current study, three staircases were randomly interleaved to measure increment thresholds for the test stimuli. This paradigm allowed us to measure the observer's increment thresholds without asking the appearance of the stimuli.

Methods

Observers

The observers were 107 normal trichromats, 2 protanopes, 1 protanomalous, 6 deuteranopes, and 7 deuteranomalous trichromats. All were diagnosed by the anomaloscope (Neitz model OT-II) and by Ishihara Pseudoisochromatic Plates and were naive as to the aim of the experiment. Of the normal trichromats, 53 were males and 54 were females. The mean age was 20.4 years (S.D. = 3.1) with a range of 18 – 36. All the color vision defectives were males with age range 14 – 61.

Stimuli

The computerized test was developed and displayed on a Sony GDM-F520 Trinitron display controlled by Radius ThunderPower 30/1600 video card and Macintosh G4 computer. The spectral power distribution and the gamma function of the phosphors were calibrated by a PhotoResearch PR650 photometer.

The display subtended a visual angle of 25° by 19° at the viewing distance of 0.87 m. The surround filled the display and its CIE chromaticity coordinates were (0.393, 0.460) at 3.1 cd/m^2 . Four 1.5° , 4.2 cd/m^2 square, static pedestals were aligned as 2×2 matrix around the center of the display separated by $15'$ with the same chromaticity as the surround. A central black fixation square subtended a visual angle of $15'$. Figure 1 shows the spatial configuration of the stimuli. A trial changed all the four squares for 133 msec; three of the four squares were incremented by 1.0 cd/m^2 (Δ pedestal) and one randomly chosen square showed a further increment of red (0.528, 0.357), green (0.299, 0.532), or yellow (0.393, 0.460). The three incremental stimuli had the same S-cone excitation.

Procedures

The increment thresholds were measured by the pedestal- Δ -pedestal paradigm with adaptive staircase procedures and a spatial four-alternative-forced-choice trial. These methods are fully described elsewhere (Pokorny et al. 1997; Smith et al. 2000; Smith et al. 2003).

The observer was seated in front of the display and asked to view the display binocularly. Automated voice instruction lasted 95 sec during which the observer adapted to the surround and the static pedestal squares. The observer initiated the trial by using the mouse. After one second, the 133 msec trial was presented and 100 msec later the cursor appeared at the center of the screen. The observer's task was to choose the square that was different from the other three, to move the cursor to that square, and to click the mouse. The cursor disappeared upon mouse click. This concluded a trial and the next trial was initiated after 1 sec. No feedback was given as to the correctness of the response. The observer was instructed to keep on responding until the program finished automatically.

The computerized test program was set up to measure the observer's increment thresholds for the three stimuli (red, green, and yellow) by three randomly interleaved staircases. Each staircase began with an obviously detectable test stimulus. The luminance of the stimulus was decreased after three correct responses and was increased upon one incorrect response on a logarithmic scale. Beginning at 0.06 log unit, the step size was halved at each response reversal until it reached 0.0075 log unit after which the step size was fixed. The first four reversals were discarded and the average of the following six reversal points were taken to estimate the threshold for that stimulus. Each observer was asked to complete two sessions of the computerized test. The results reported here are the means of the two sessions for each of the three stimuli. One session took 4 to 6 minutes to complete excluding the automated voice instruction. No observer chose to take a rest between the two sessions although this was offered. The voice instruction was omitted in the second session since the observer was already familiar with the procedure.

Informed consent was obtained before participation. Procedures adhered to the tenets of the Declaration of Helsinki, and the protocol was approved by the Institutional Review Boards of the California State University, Fullerton and the Biological Sciences Division, The University of Chicago.

Results

Normal trichromats showed substantially higher sensitivity for R and G (chromatic) than for Y (luminance) test stimuli, whereas red-green color defectives showed reduced sensitivities for the chromatic stimuli. This result can be attributed to L-M cone signal detection in the parvocellular pathway. The increment thresholds for the luminance stimulus (ΔY) did not differ substantially among observers of different color vision types.

Figure 2 shows the frequency distribution of the Sloan notch as expressed by $\log(\Delta Y/\Delta R)$. Open bars indicate normal trichromats, solid bars indicate protanopes, right-downward stripe bar indicates a protanomalous, shaded bars indicate deuteranopes, and right-upward stripe bars indicate deuteranomalous. Results from 107 normal trichromats showed a mean Sloan notch of 0.654 (S.D.=0.123) log unit. We applied the goodness-of-fit χ^2 test and the obtained χ^2 was 17.39 with $df=11$ and $\alpha=0.05$. The critical χ^2 was 19.68, thus the observed frequency distribution of the Sloan notch among normal trichromats was not significantly different from a normal distribution. The minimum Sloan notch among normal trichromats was 0.341. The Sloan notch for deuterans ranged from -0.062 to 0.353 , and for protans from -0.103 to -0.119 . Three normal trichromats with the smallest Sloan notch and two deuteranomalous form an intermediate cluster of Sloan notch between the majority of normal trichromats and obviously color defective observers. The anomaloscope matching range of those two deuteranomalous was 3 or 4 units and they misread only 5 or 4 Ishihara pseudoisochromatic plates. These consistent results from various measures indicate that these two deuteranomalous are functionally trichromatic.

If ΔY was mediated by the same mechanism as ΔR and ΔG , as presumed in dichromats, we should be able to predict ΔY from linear sum of ΔR and ΔG . ΔY_p was calculated in red-green phosphor space. The three stimuli, R near the red phosphor, G near the green phosphor, and Y as a sum of the two phosphors can be all expressed in (G,R) phosphor luminance. The predicted ΔY_p occurs at the intersection of two lines, the Y luminance line and a line connecting ΔR and ΔG . The ratio $\Delta Y/\Delta Y_p$ would be close to 1, or $\log(\Delta Y/\Delta Y_p)$ would be close to 0 if ΔY was mediated by the same mechanism as ΔR and ΔG . This is predicted for color vision defective observers. On the other hand, the size of the Sloan notch ($\log(\Delta Y/\Delta R)$) would be positively correlated with $\log(\Delta Y/\Delta Y_p)$ among normal trichromats, indicating that the more sensitive parvocellular, chromatic pathway, the higher ΔY compared to ΔR or ΔY_p .

Figure 3 shows the scatter plot of $\log(\Delta Y/\Delta Y_p)$ vs the Sloan notch. Open circles show results for normal trichromats, solid circles indicate those for protanopes, a solid triangle for the protanomalous trichromat, solid squares for deuteranopes, and diamonds for deuteranomalous trichromats. As expected, the ratio of $\log(\Delta Y/\Delta Y_p)$ for color vision defective observers except for the two deuteranomalous was close to 0.0 (mean = -0.007 , S.D. = 0.046). For normal trichromats the correlation factor between the two measures was 0.913, indicating a strong correlation.

Discussion

Advantages of the computerized test described here include that it is easy to administer, that a naïve observer can complete the task without fatigue, and that it does not ask an observer about the appearance of the stimuli. Indeed, the interview with dichromatic observers after the experiment revealed that they did not even know that there were three different kinds of stimuli. All the stimuli appeared pure luminance changes to them. Further it is easy to implement with any desk top computer that has a CRT monitor.

The computerized test devised in this study allows us to assess color vision easily and quickly. The testing time is similar to that of screening plate tests. The Sloan notch as defined by $\log(\Delta Y/\Delta R)$ proved capable of distinguishing normal and color defective observers. The majority of normal trichromats possessed the Sloan notch of 0.42 or higher. A small number of normal trichromats (3 out of 107) and some sensitive deuteranomalous trichromats showed the Sloan notch between 0.30 and 0.37. Other color vision defectives showed Sloan notch less than 0.16. Greater numbers of deutan and protan observers need to be tested to establish an optimal screening criterion. However our result compares favorably with screening plate tests and is probably more sensitive than the Farnsworth Panel D-15.

The results within the color defectives suggest that the test would also have a high coefficient of association for qualitative classification. A criterion Sloan notch of -0.10 would completely differentiate protans and deuterans. Yet this must be treated with precautions because we did not have many color defective observers. This is a great improvement compared with screening plate tests because the computer test allows a direct estimate of spectral sensitivity. It is unlikely that the test can differentiate dichromats and anomalous trichromats, but it can differentiate functional trichromats (all the normal trichromats and some anomalous trichromats) and functional dichromats (the majority of anomalous trichromats and all the dichromats) because the test assesses the depth of the Sloan notch. Color-weak normal trichromats and some sensitive anomalous trichromats show a Sloan notch value between that of the majority of normal trichromats and functional dichromats.

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Figure 1.
Spatio-temporal configuration of stimuli.

Figure 2.

The frequency distribution of the Sloan notch as expressed by $\log(\Delta Y/\Delta R)$. Open bars indicate normal trichromats, solid bars indicate protanopes, right-downward stripe bar indicates a protanomalous trichromat, shaded bars indicate deuteranopes, and right-upward stripe bars indicate deuteranomalous trichromats.

Figure 3.

The scatter plot of $\log (\Delta Y / \Delta Y_p)$ vs the Sloan notch. Open circles show results for normal trichromats, solid circles indicate those for protanopes, a solid triangle for the protanomalous trichromat, solid squares for deutanopes, and diamonds for deuteranomalous trichromats.