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A simple behavioral demonstration of blue-cone anisotropy: Distance-induced tritanopia on standard color vision tests

GERALD M. LONG and J. PORTER TUCK
Villanova University, Villanova, Pennsylvania

In the course of a larger research program examining popular color-vision tests, the very powerful role of varying viewing distance was demonstrated with color-normal observers. More importantly, the effect of increasing distance was shown to be particularly evident for items designed for detection of blue-yellow dichromacy. This is attributed to distance-induced tritanopia, which in turn reflects the unusual distribution of the "blue" cones in the retina. The utility of this finding for the simple demonstration of a nonintuitive aspect of retinal anatomy is discussed.

There has been a growing realization in recent years that many of the traditional screening tests used in the assessment of color vision differ greatly both in precision and in susceptibility to even modest variations in viewing conditions. The most common of these tests are the numerous versions of the pseudoisochromatic plates first introduced in the 1870s by Stilling (see the reviews of color vision testing by Murray, 1943, and the National Research Council, 1981). Examples from the most popular ones can be found in many general psychology texts, in discussions of color vision and color-vision deficits. The individual plates consist of a figure, usually a digit, printed in a particular color and surrounded by a cluster of background dots of different colors. Theoretically, these background dots are of colors that fall on the confusion axes of the color in the target dots. Only if an observer does not confuse such colors will he or she be able to identify the target figure. Hence, the tests are used to identify observers who exhibit the types of confusions characteristic of red-green and yellow-blue dichromacy.[1]

In the last few years, our lab has been examining the comparability of the various "plate tests" that are on the market, in order to determine the sensitivity of these popular screening devices to variations in viewing conditions. For example, Long, Lyman, and Tuck (1985) varied viewing distance, viewing duration, and stimulus clarity on the pseudoisochromatic tests published by the American Optical Corporation (1965), Dvorine (1953), and Ishihara (1982). They found that the three tests differed greatly not only in terms of the absolute level of performance exhibited by color-normal observers but also in sensitivity to the manipulations in viewing conditions. Other work has essentially replicated these findings while extending them to other viewing conditions, such as illumination (Long et al., 1984), and to other plate tests of color vision (Somerfield, Long, Tuck, & Gillard, 1989; Tuck & Long, 1986). These other tests include the *Standard Pseudoisochromatic Plates for Congenital Vision Defects* (SPP-C; Ichikawa, Hukami, Tanabe, & Kawakami, 1978), the *Standard Pseudoisochromatic Plates for Acquired Vision Defects* (SPP-A; Ichikawa, Hukami, & Tanabe, 1983), and the *City University Colour Vision Test* (CUCVT; Fletcher, 1980). This last test differs from the traditional pseudoisochromatic ones in that it consists of individual plates composed of four dots surrounding a central dot. The observer's task is to choose the surrounding dot that most closely matches the central dot.

One consistent conclusion that we and others have drawn from this work has been that additional visual processes beyond simple color discrimination play an important role in these popular screening tests, and that these other processes may vary widely from one test to another. For example, several authors have suggested that acuity demands may be quite different across ostensibly similar tests (e.g., Holland, 1972; Tuck & Long, 1986). Over 20 years ago, Lakowski (1966, 1969a, 1969b) argued that several of the plate tests differed in the degree of contrast between the figure dots and the background dots, thus introducing the unknown influence of chromatic discriminative ability, which can differ widely among color-normal observers (Farnsworth, 1943).

In the course of this broader research program, in which we were attempting to identify other visual processes underlying performance on these color-screening devices, we uncovered an interesting behavioral consequence of one form of retinal asymmetry. The particular focus of this work was on the impact of the retinal size of the critical details of the stimuli on several of the plate tests of color vision enumerated above. It had been established previously that varying the viewing distance had a marked impact on performance on some of the plate tests (e.g., Long et al., 1985. Although this result (as well as others) was attributed to the differential acuity demands of some

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of the tests, another process was hypothesized to be involved on those tests that particularly assess yellow-blue dichromacy. This process is "small-field tritanopia," which in turn reflects the unusual distribution of the short-wavelength (blue) cones across the retina. It is now known that the central fovea is devoid (or nearly so) of all blue cones, which, unlike the mid- and long-wavelength cones, exhibit their maximum density at about 1° eccentricity (Boynton, 1988). This anatomical arrangement raises the distinct possibility that, under certain circumstances, critical items in the yellow-blue tests may fall on retinal areas that do not permit color discrimination by color-normal observers. This hypothesis has been examined formally by Tuck and Long (1989). We wish to summarize a portion of that work here, because of the straightforward and easily arranged demonstration of small-field tritanopia that it permits. Such a demonstration may prove useful as an interesting teaching device for the presentation of an aspect of human visual anatomy.

METHOD

Subjects

One hundred and eight college students from general psychology at Villanova University participated in individual 30-min sessions, in partial fulfillment of a course requirement. Only observers with no known color problems were asked to volunteer, and each volunteer was further screened (see below) to ensure that any individual with even modest color problems was excluded.

Apparatus and Procedure

Each observer was initially prescreened for normal color vision on the *Farnsworth Dichotomous Test for Color Blindness* (D-15, Farnsworth, 1947) and on two of the "hidden digits" plates from the Ishihara Test, which presumably can be identified only by color-defective individuals.

A single error on the D-15 or the identification of either hidden digit resulted in the individual's exclusion from the study. Each observer was then randomly assigned to one of six possible groups, which were defined by the factorial combination of two viewing durations (0.5 or 3.0 sec per plate) and three viewing distances (46, 77, and 152 cm). Viewing duration was controlled by means of a Lafayette timer (Model 5002A) linked to an Ealing shutter (Model 22-8437) positioned in front of the observer's right eye. The left eye was occluded. Viewing distance was controlled with a chin- and headrest located at the appropriate distance for that observer.

The SPP-A and the CUCVT consist of 10 individual plates each. On the former, the observer reports the digits that can be identified on each plate; on the latter, the observer reports the surrounding dot that most closely matches in color the central target dot. Before each test was administered under the viewing conditions appropriate for each given observer, the observer was shown a practice plate from each test in order to familiarize him or her with the task to follow. All tests were administered under lighting provided by two side-by-side Easel Lamps, to ensure appropriate illumination.

RESULTS

Each of the tests can be scored for tritan errors (i.e., blue-yellow confusions) and nontritan errors. Hence, the data for the 108 observers consisted of the proportions of tritan and nontritan errors made under the six viewing conditions that were employed. These data were analyzed separately within two 2 (duration) × 2 (distance) × 2 (type of error) analyses of variance, with the last factor the only within-subjects variable. The analyses of the CUCVT errors revealed significant main effects of duration [$F(1,102) = 83.42$, $p < .0001$] and distance [$F(2,102) = 51.37$, $p < .0001$]. Consistent with the results of several previous studies using other types of plate tests (e.g., Long et al., 1985), the proportion of errors made by color-normal subjects increased as viewing duration decreased and as viewing distance increased. The main effect of error type was also significant [$F(1,102) = 16.33$, $p < .002$]; but, most importantly, the interaction of error type × distance shown in Figure 1 was also highly significant [$F(2,102) = 18.25$, $p < .0001$]. In other words, as hypothesized, the effect of increasing viewing distance had a far more pronounced effect on the tritan error rate than on the nontritan error rate. Also consistent with this hypothesis was the significant triple interaction of error type × distance × duration interaction [$F(2,102) = 7.25$, $p < .0002$]. This resulted from the far more pronounced error type × distance interaction with the 0.5-sec per plate duration than with the 3.0-sec per plate duration. We attribute this to the greater impact of the distance-induced tritanopia under conditions in which scanning of the stimuli was limited due to the restricted duration.

The analysis of the errors from the SPP-A test produced basically similar findings. The main effects of duration [$F(1,102) = 191.88, p < .0001$], distance [$F(2,102) = 74.40$, $p < .0001$], and error type [$F(1,102) = 61.57$, $p < .0001$] were highly significant. And, again as predicted, the interaction of error type × distance shown in Figure 2 was highly significant [$F(2,102) = 13.02$, $p < .0001$]. As is evident in the figure, the adverse effect of increasing viewing distance was much more pronounced for the tritan errors than for the nontritan er-

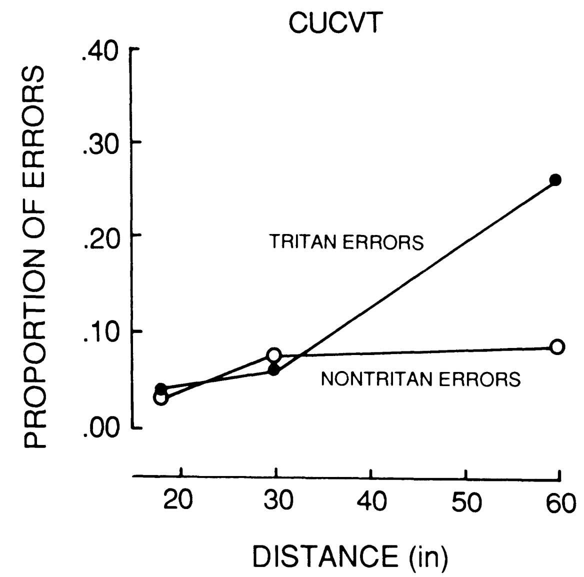

Figure 1. The mean proportion of errors by color-normal observers on the CUCVT as a function of viewing distance. For clarity, the results from the 0.5- and the 3.0-sec/plate durations have been averaged together.

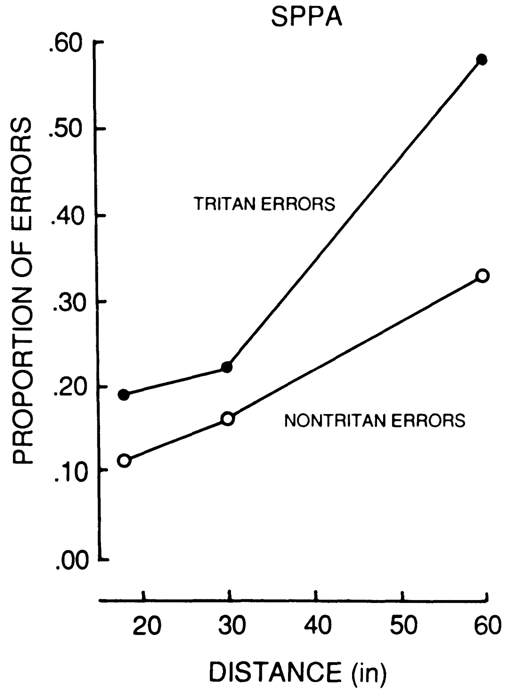

Figure 2. The mean proportion of errors by color-normal observers on the SPP-A as a function of viewing distance. For clarity, the results from the 0.5- and the 3.0-sec/plate durations have been averaged together.

ror rate. Unlike the findings with the CUCVT, the triple interaction of error type × distance × duration was not significant [$F(2,102) = 1.33$, $p > .05$]. However, the significantly larger size of the target digits in the SPP-A compared to the individual dots in the CUCVT may have rendered the former much less sensitive to limited scanning than the latter.

DISCUSSION

Within the broader context of a research program examining the potential role of visual processes (in addition to color confusions) that may affect performance on color-vision tests, we have established the clear impact of distance-induced tritanopia with color-normal observers. As we have detailed elsewhere (Tuck & Long, 1989), the immediate practical implication of this finding is the reaffirmation of the criticality of viewing conditions with the standard color-assessment procedures. The popular color tests on the market differ markedly in sensitivity to even modest variations in viewing conditions. Given the widely varying samples from the population to whom these tests are administered, and the special circumstances that often obtain with such groups (e.g., children, retarded individuals, or the elderly), the conditions recommended in the test batteries, which are sometimes vague to begin with, are often difficult to maintain.

The primary reason for the presentation of these results in the present forum is pedagogical. The findings presented in Figures 1 and 2 reflect an interesting aspect of human visual anatomy. In recent years, the blue cones have been found to differ from the green and red cones in several respects, not the least of which is their unusual retinal distribution (see Boynton, 1988). The apparent absence of blue cones from the central fovea is both fascinating and nonintuitive. Hence, a clear behavioral demonstration of this unusual anatomical arrangement serves as a powerful complementary result of the present work. Within an educational context, the demonstration of distance-induced tritanopia with readily available color stimuli may render the facts considerably more memorable—much as the demonstrations of color zones and the blind spot do for other points of retinal anatomy. Furthermore, the simplicity of the stimuli that make up the CUCVT, which essentially involves five small dots per card, would appear to be easy to mimic and/or modify for a classroom demonstration if the formal test is not available.

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NOTE

1. Some plate tests contain items in which the color-blind individual is theoretically able to read a digit that is invisible to the color-normal observer. However, such "hidden digits" plates are rather rare and are found on only some of the common tests (see Lakowski, 1969a, 1969b).

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