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The color of night: Surface color categorization by color defective observers under dim illuminations

JOEL POKORNY,[1] MARGARET LUTZE,[1] DINGCAI CAO,[1] AND ANDREW J. ZELE[2]

[1]Department of Ophthalmology & Visual Science, The University of Chicago, Chicago, Illinois
[2]School of Optometry and the Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia

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Abstract

People with normal trichromatic color vision experience variegated hue percepts under dim illuminations where only rod photoreceptors mediate vision. Here, hue perceptions were determined for persons with congenital color vision deficiencies over a wide range of light levels, including very low light levels where rods alone mediate vision. Deuteranomalous trichromats, deuteranopes and protanopes served as observers. The appearances of 24 paper color samples from the OSA Uniform Color Scales were gauged under successively dimmer illuminations from 10 to 0.0003 Lux (1.0 to −3.5 log Lux). Triads of samples were chosen representing each of eight basic color categories; "red," "pink," "orange," "yellow," "green," "blue," "purple," and "gray." Samples within each triad varied in lightness. Observers sorted samples into groups that they could categorize with specific color names. Above −0.5 log Lux, the dichromatic and anomalous trichromatic observers sorted the samples into the original representative color groups, with some exceptions. At light levels where rods alone mediate vision, the color names assigned by the deuteranomalous trichromats were similar to the color names used by color normals; higher scotopic reflectance samples were classified as blue-green-grey and lower reflectance samples as red-orange. Color names reported by the dichromats at the dimmest light levels had extensive overlap in their sample scotopic lightness distributions. Dichromats did not assign scotopic color names based on the sample scotopic lightness, as did deuteranomalous trichromats and colour-normals. We reasoned that the reduction in color gamut that a dichromat experiences at photopic light levels leads to a limited association of rod color perception with objects differing in scotopic reflectance.

Keywords: Rod color, Dichromats, Photopic, Mesopic, Scotopic

Introduction

At the eighteenth symposium of the International Colour Vision Society, we reported on the color appearances of 24 simultaneously presented paper color samples, three each from eight basic color categories: "red," "pink," "orange," "yellow," "green," "blue," "purple," and "gray." Color normal trichromatic observers sorted the samples into groups by color category and named the color associated with each group. The procedure was repeated under various illuminations including dim light levels where rods alone mediated vision (Pokorny et al., 2006). The reported color names by the trichromatic observers with successive reductions in the illumination level were interpreted in terms of the contributions of the different photoreceptor classes. At light levels where all three cone photoreceptor classes were operational, (≥−0.5 log Lux), observers sorted the samples into the originally chosen basic color categories with few exceptions. At intermediate light levels (−2.0 to −1.0 log Lux), rods and L-cones mediated perception and the red and orange samples were usually identified as either red or orange with the remaining samples grouped into two categories associated with the relative sample scotopic lightness, which is defined as summed spectral energy weighted by the scotopic luminance function, $V'(\lambda)$. At the lowest light levels (≤−2.5 log Lux), where rods alone mediated perception, there were salient and diverse color percepts that could be reliably assigned on the basis of the relative sample scotopic lightness; for samples above threshold, those with lower reflectance were classified as red or orange and the higher reflectance samples as green, blue-green, blue, or achromatic. At the lowest illumination level, presenting the color paper samples individually, thereby eliminating contextual cues from the other samples resulted in each of the suprathreshold samples being identified as blue-green. Thus, the colors seen under conditions where rods exclusively mediate vision are relational, with low-reflectance, samples identified using longer-wavelength descriptors and higher reflectance samples identified using shorter-wavelength descriptors. The scotopic color name for any given

Address correspondence and reprint requests to: Joel Pokorny, Visual Science Laboratories, The University of Chicago, 940 East 57th Street, Chicago, IL. E-mail: j-pokorny@uchicago.edu

sample will therefore change depending on the reflectance of additional samples in the field of view.

We hypothesized that with input solely from rods, and when confronted with an array of objects differing in scotopic lightness, the visual system of a color-normal observer estimates probable colors based on natural visual experience (Pokorny et al., 2006). Given developmental and long-term experience with viewing familiar objects in the natural environment under both bright and dim illuminations, the observer's visual system may infer that at low light levels brighter appearing objects are richer in short wavelength light compared to dimmer appearing objects. A test of this idea is to perform the same color appearance experiment on observers whose cone systems are not capable of conveying the same richness of information about the chromatic properties of objects; that is, observers with a congenital color vision deficiency. If developmental and long-term experience plays a role in the color appearances seen by color-normal observers under conditions where rods alone mediate vision, then color defective observers would be expected to fail to use the relational longer- and shorter-wavelength descriptors associated with dimmer and brighter appearing samples. The results from the current study demonstrate this to be the case for the dichromatic observers, whereas the response pattern of deuteranomalous trichromats is similar to that of color normal trichromatic observers.

Materials and methods

Stimuli and apparatus

This experiment employs the same apparatus and methodology as in the experiment with color-normal observers (Pokorny et al., 2006).

The stimuli were 24 paper color samples from the Optical Society of America Uniform Color Scales (OSA-UCS). The colors chosen for this study were triads of samples representing each of the eight basic color categories used by color-normal observers to describe the non-dark appearing colors (Boynton & Olson, 1987); "red," "pink," "orange," "yellow," "green," "blue," "purple," and "gray." The samples within each color triad varied in lightness. Calibration details including the chromaticities and the relative scotopic and photopic luminances of the samples are given in the earlier publication. The 50-mm square samples were placed in matt black mounts that could be moved around on matt black surfaced viewing table. Each sample subtended 8° to 10° of visual angle when viewed from 0.30–0.35 m. The apparatus allowed fine adjustment of light level over a wide light level range.

Observers

Color defective observers were recruited by advertisements placed on campus bulletin boards. Color vision was assessed with the Neitz OT anomaloscope and the Ishihara pseudoisochromatic plate test. By these means, we identified two deuteranomalous trichromats (DA), three deuteranopes (D), and two protanopes (P) to serve as observers. All were male undergraduate students. The Institutional Research Board at the University of Chicago approved all procedures. Data from four color-normal observers (Pokorny et al., 2006) are included for comparison.

Procedure

All samples were simultaneously presented on the viewing surface. The appearances of the samples were gauged under successively dimmer illuminations in 0.5 log unit steps over a 3.5 log unit range from 1 to 0.0003 Lux (0.0 to −3.5 log Lux). Sufficient time for adaptation, 10 min, followed each decrease in illumination. At each light level, the observer was initially presented with a random aggregation of the samples, which he then sorted into groups that could be categorized with specific color names. There were no restrictions imposed as to the color names an observer could use. The experiment for all light levels was completed in a 2.5 h session; each observer participated in three sessions.

Data analysis

For each color defective observer, a total of 576 observations (eight illumination levels, 24 color samples, three repeats) were recorded. Data analysis was performed on the modal responses of the three repeats for an observer for each color sample. The mode was defined as a color name reported at least two times within the three repeats. Color samples without a modal response (i.e., the observer reported three different color names on the three repeats) were excluded from the analysis. From the earlier study on color-normals, 6% (61 of the 960 combinations) of illumination × color sample × observer were excluded because of a lack of consensus. Here, 11% (143 of 1344 combinations of eight illuminations × 24 samples × 7 observers) of the color defective combinations did not yield a mode, with low non-modal rate (0.5%) at the highest illumination level (0.0 log Lux) and higher non-modal rate (8%–16%) at lower light levels.

Results

Fig. 1 shows the response categories used to describe the samples representing each of the eight basic color categories. Each panel represents a single basic color category; response names are shown on the abscissa with light level on the ordinate. Data for color-normals (N), deuteranomalous trichromats (DA), deuteranopes (D), and protanopes (P) are presented from the top to the bottom rows, respectively.

The deuteranomalous trichromats, protanopes, and deuteranopes all employed a diversity of color terms at all light levels. At the lowest light levels, the deuteranomalous trichromats showed response patterns more similar to the color-normals. At the higher light levels (≥ −0.5 log Lux), the dichromatic and anomalous trichromatic observers sorted red, orange, yellow, green, purple, and blue samples into the original color-normal defined representative color groups, with some exceptions. Differences from normal sorting were found for the gray samples, which were identified as either gray or green, and the pink samples, which were identified, as pink, purple, green, or gray.

At the intermediate light levels between −2.0 and −1.0 log Lux, color names assigned by the dichromats and anomalous trichromats were similar to those of the color-normal observers; red and orange samples were usually identified as either red or orange, and the remaining samples tended to be grouped into two categories, associated with the scotopic sample reflectance. The major difference was that color defective observers frequently interchanged the purple and pink color names, and the green and gray colour names from their respective samples.

At the three lowest light levels (≤−2.5 log Lux), where rods alone mediated vision and where the color-normal observers assigned color categories reliably on the basis of the sample scotopic reflectance, color defective observers also used a variety of color terms. To summarize major data trends, we separated the distribu-

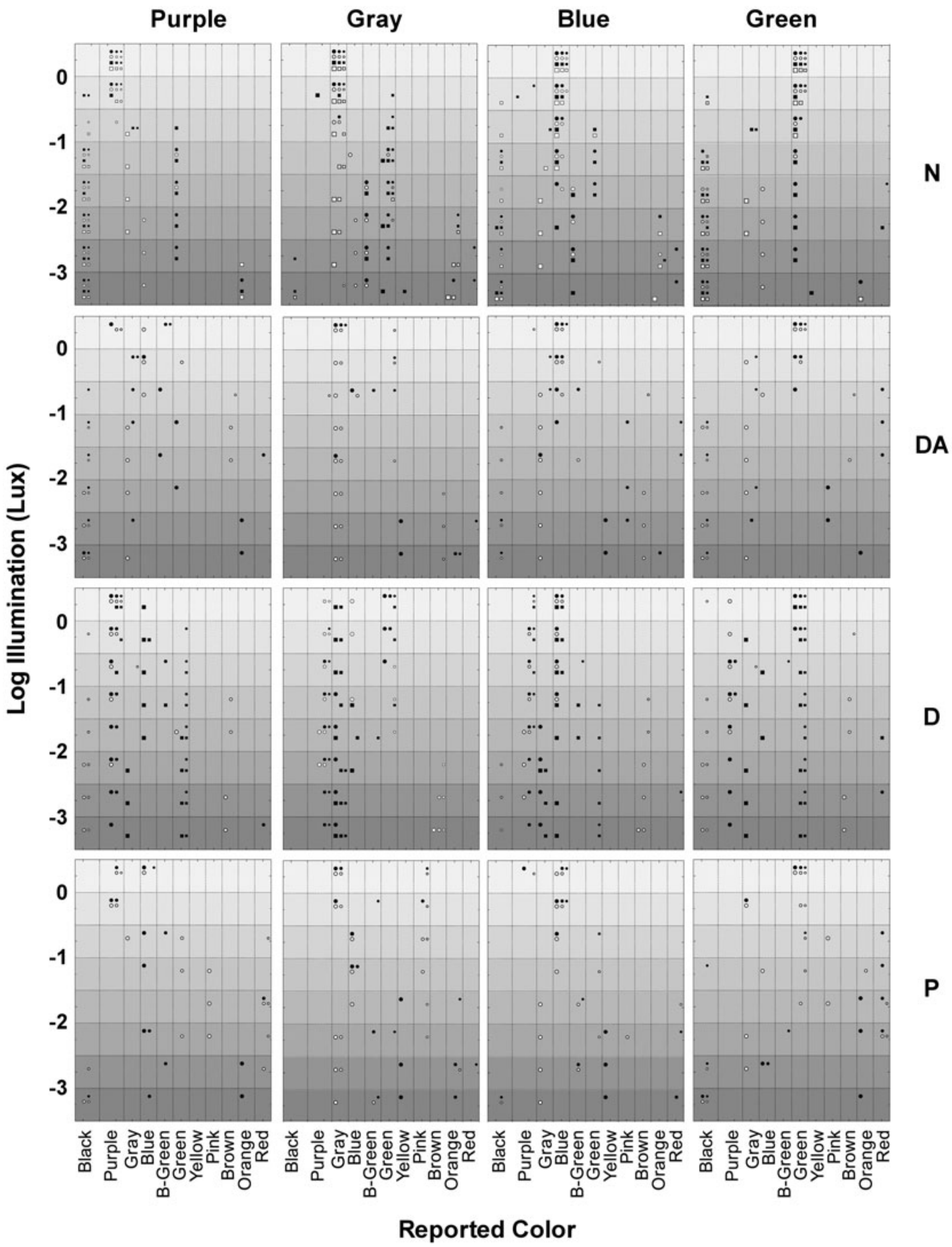

Fig. 1. The reported color of the eight ("gray," "purple," "blue," and "green" in Fig. 1A; "yellow," "pink," "orange," and "red" in Fig. 1B) color sample categories (abscissa) as a function of photopic illuminance (ordinate) for normal trichromats (N), deuteranomalous trichromats (DA), deuteranopes (D) and protanopes (P). Each column shows data for one color sample category as labeled on top of the figure with different symbols representing different observers. The symbol size refers to the lightness of the OSA-UCS sample, with the smallest symbols representing the lowest lightness, and the largest symbols the highest lightness. The leftmost column in each panel shows samples reported as black (below detection threshold). Normal trichromats: AJZ (●); DC (○); JP (■); ML (□). Deuteranomalous trichromats: DM (●); TB (○). Deuteranopes: AM (●); IT (○); KS (■). Protanopes: ES (●); MP (○).

tions of relative sample scotopic lightness based on whether the reported color name was associated with the mid- and short-wavelength region of the spectrum, or the long-wavelength region of the spectrum. Fig. 2 shows the distributions of the relative sample scotopic lightness for reported black (including reported purple for deuteranopes), red-orange-pink, and blue-green-gray color names for observers with different types of color vision. Clearly, with the exception noted in the figure caption, for color-normals and for

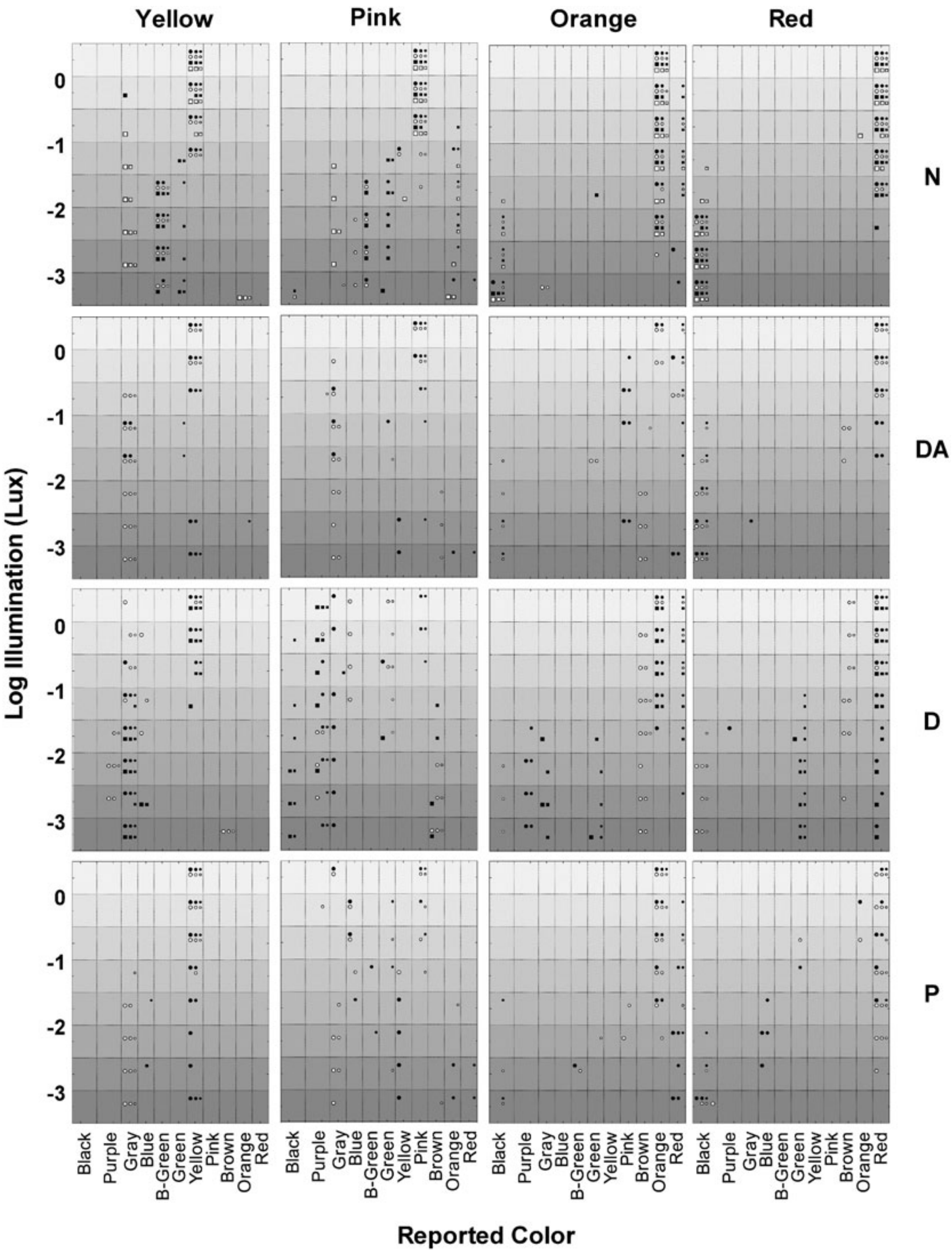

Fig. 1. continued

deuteranomalous trichromats (upper two rows), samples with higher scotopic lightness were classified as blue-green-grey (triangles) and samples with lower lightness as red-orange (squares). Note that for color-normal observers at the lowest light level, the high sample lightness assigned to the red-orange category reflects the sorting responses of one observer (ML). Mann-Whitney U tests at each light level show that all samples classified as blue-green-grey had significantly higher lightness than samples classified as red-orange ($p < 0.01$) for color-normals (observer ML's data were not included in the analysis) and deuteranomalous trichromats. The remaining samples were below threshold (circles). For dichromats (D and P), however, the distribution of the relative sample scotopic lightnesses with the reported red-orange and blue-green-gray color names overlap extensively, especially for deuteranopes. Mann-Whitney U tests at each light level show that all samples classified as blue-green-grey had significantly higher lightness than samples classified as red-orange for protonopes ($p < 0.05$), but not for deuteranopes ($p > 0.08$).

The black category was used in different ways by the different types of observers. The color-normal data show a systematic

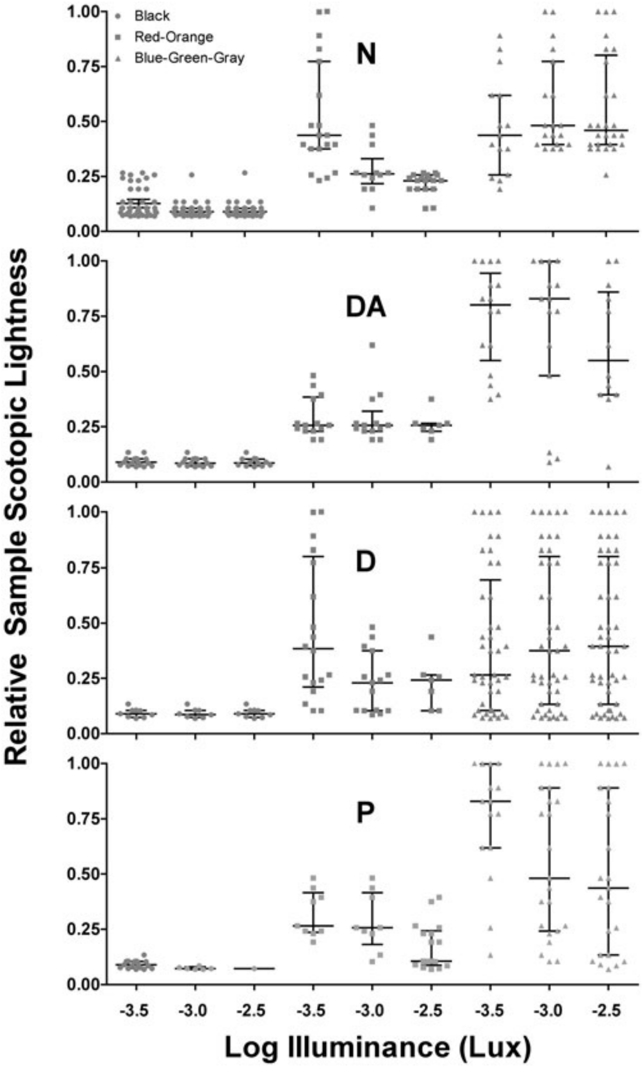

Fig. 2. The distributions of the relative sample scotopic lightness with samples reported color names as black (below threshold, (●) red-orange (■), and blue-green-gray (▲)) at light levels ≤−2.5 log Lux for observers with different types of color vision. In each panel, the horizontal bars indicate the median with associated interquartile range (from the 25th to 75th percentile). The illuminance levels are shown in the abscissa in each panel. The data for observers within the same color vision type were combined. Note that at all three scotopic light levels, the distributions of the relative sample scotopic lightness of the same reported color name are similar therefore they are plotted next to each other. For the color-normal observers at the lowest light level, the samples with relatively high scotopic lightness assigned to the red-orange category all reflect the sorting responses of one observer (ML).

decrease in the use of the black category with increasing light level (58%, 54%, and 44%). This is the expected pattern if black is reserved for samples below visual threshold. The deuteranomalous and deuteranopic observers used black with roughly the same consistency across light levels, about 35% for deuteranomalous observers and 13% for deuteranopes. The protanopes showed a pattern comparable to that of the color-normal observers, however, there were fewer samples assigned to the black category (41%, 16%, and 2%). Given red objects appear darker to protanopic than to color-normal observers; the protanopes assigned many below threshold stimuli to the red-orange category. In a sense this appears comparable to what the color-normal observers were doing but at the intermediate and higher scotopic light levels (−3.0 and −2.5 log Lux) where the protanopes assigned many of the low scotopic lightness samples to the blue-green-gray category.

Discussion

In color naming studies, it has been shown that dichromats can name colors in fair agreement with color-normal observers (Scheibner & Boynton, 1968; Nagy & Boynton, 1979; Montag & Boynton, 1987; Montag, 1994). The physiological underpinning for trichromacy likely varies with stimulus conditions, with rods playing a role as a third photoreceptor class for spatially extended or peripherally located stimuli under moderate to dim light conditions (Smith & Pokorny, 1977) or the presence of an additional but poorly represented cone type (Nagy, 1980; Breton & Cowan, 1981; Frome et al., 1982). The middle and long wavelength photopigment spectra of anomalous trichromats are more closely spaced than those of color-normals, leading to degraded color naming (Smith et al., 1973) and a severe compression of perceptual color space along the r-g dimension (Müller et al., 1991). Here for the first time, we report color naming in color defective observers at scotopic light levels.

Under very dim light levels where rods alone mediate vision, color-normal observers consistently report color names based on relative sample scotopic lightness. We speculated that developmental and long-term experience with viewing familiar objects in the natural environment under dim illumination allowed color normal observers to infer that bright appearing objects are richer in shorter wavelength light compared to dim appearing objects. Our results show that at photopic luminance levels, color defective observers used most basic color terms in the same way as color-normal observers. Unlike color-normal observers, at scotopic luminance levels the assigned color categories of the color defective observers do not reveal an association of scotopic brightness and spectral composition. Dichromats lifetime experience with a much reduced color gamut at photopic light levels may contribute to their limited association of rod color perception with the spectral composition of objects differing in scotopic reflectance.

Acknowledgments

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