Color naming, lens aging, and grue: What the optics of the aging eye can teach us about color language

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Abstract

Many languages without separate terms for "green" and "blue" are or were spoken in locations receiving above-average exposure to ultraviolet-B (UV-B) radiation. Lindsey and Brown (2002) propose that this correlation is caused by premature lens aging. When younger observers view simulated paint chips filtered through the equivalent of an older observer's lens – removing much short-wavelength light – they use the term blue less often than when describing the unfiltered versions. Some stimuli that were called blue without simulated aging were called green when filtered. However, when we tested older observers with known ocular media optical densities we found no difference between older and younger subjects in the proportion of blue color-name responses. Color naming for stimuli that were nominally green, blue-green or blue was virtually identical for older and younger observers when viewing the same (unfiltered) stimuli. Our results are inconsistent with Lindsey and Brown's (2002) lens brunescence hypothesis.

Introduction

Most humans can discriminate millions of colors, yet in every language studied systematically, the number of basic color terms is comparatively small. In English, for example, there are 11 basic color terms (BCTs), i.e., black, white, red, yellow, green, blue, purple, brown, orange, pink, and gray (Berlin & Kay, 1969). BCTs refer to the smallest collection of simple words with which a speaker can name any color. A few languages have more than 11 BCTs: Russian has distinct BCTs for light blue and dark blue, Hungarian for light red and dark red, but many languages have fewer. Welsh and most other Celtic languages do not have distinct BCTs for green and blue (Lazar-Meyn, 2004), and the same is true for almost all unwritten languages. Color term distribution is not random. Rather, there is a distinct tendency for languages to evolve color terms in a particular order. For example, no language is known to have distinct words for blue and green and yet fail to distinguish red and yellow. The origins and mechanisms underlying the regularity of color-naming across languages has been the topic of considerable investigation (e.g., Heider, 1972; Kay & McDaniel, 1978; Kay & Maffi, 1999) and debate (e.g., Hickerson, 1975; Lucy, 1997; Davidoff, Davies & Roberson, 1999).

Recently, Lindsey and Brown (2002) have offered an interesting hypothesis to explain why some languages lack BCTs that distinguish green and blue. According to their argument, most so-called grue languages (those with a single term covering both green and blue) occur in geographical locations closer to the equator or at higher elevations and receive above-average levels of ultraviolet-B (UV-B) radiation from the sun. High UV-B exposure is linked to accelerated ocular media aging, most particularly of the crystalline lens (Werner, Peterzell & Scheetz 1990; Young, 1991; Javitt & Taylor, 1994). As the crystalline lens ages, a process known as brunescence occurs. The lens becomes denser and more opaque, allowing less light to reach the retina, especially at shorter wavelengths (Weale, 1988). Individuals experiencing premature lens aging would receive less short-wavelength light at the retina when viewing the same stimuli as people with more transparent lenses. Lindsey and Brown (2002) argue that this reduced short-wavelength light exposure would reduce the need for the color term "blue," usually assigned to stimuli predominantly composed of energy at shorter visible wavelengths.

Thus, they propose that languages spoken by cultures located in high UV-B areas would tend to be grue languages. In support of this hypothesis, Lindsey and Brown (2002) performed a color-naming experiment in which they simulated the effects of lens brunescence in younger individuals. This simulation took advantage of the lens-aging model of Pokorny, Smith and Lutze (1987) to transform stimulus chromaticities to simulate the effects of optical aging. Younger observers were shown simulated Munsell chips (a set of color standards) made yellower and darker in the exact proportions prescribed by the Pokorny, et al. (1987) lens model to simulate ages between 50-100 years. As predicted by Lindsey & Brown's (2002) lens brunescence hypothesis, observers used the term "blue" progressively less often as the simulated lens was increasingly aged. Chips previously called "blue" were called "green" or "gray" after being transformed by simulated aging. Lindsey and Brown (2002) concluded that the results of this experiment show that premature lens brunescence could lead to a reduced need for the term blue. This argument has created considerable interest and some controversy (e.g., Lazar-Meyn, 2004; Lindsey and Brown, 2004; Regier and Kay, 2004).

While Lindsey and Brown's (2002) aging simulation was mathematically consistent with a valid model of lens brunescence, the effects of lens aging can be tested more directly. This can be achieved by testing individuals of various chronological ages and, thus, a range of ocular media optical densities (ODs). The results of this more direct test could differ from a simulation. Younger observers viewing stimuli designed to simulate the optics of the aging eye experience lower light levels and higher proportions of long-wavelength light for a matter of minutes. Older individuals with brunescent lenses live with their optics continuously, as do people with more brunescent lenses from high UV-B areas. While Lindsey and Brown (2002) did have observers briefly (3 minutes) adapt to the background color previous to the experiment, chromatic adaptation can operate on very long time scales, on the order of days (Neitz, Carroll, Yamauchi, Neitz, & Williams, 2002) or even months (Delahunt, Webster, Ma, & Werner, in press). Chromatic adaptation has the effect of changing how the visual system interprets the light reaching each of the three cone photoreceptor types (Jameson & Hurvich, 1956), which can largely compensate for the changes in the average spectral distribution of light reaching the retina (Uchikawa, Uchikawa, & Boynton, 1989). Thus, while such a simulation *can* closely replicate the pattern of wavelengths reaching the observer's retina with differing ocular media ODs, it is unlikely to accurately simulate the perceptual experience of observers with naturally yellowed lenses.

To test Lindsey and Brown's (2002) lens-brunescence hypothesis we compared color naming in individuals with a range of known ocular media ODs. We did this in two ways. In one set of conditions, we tested color naming in groups of younger and older observers with the same standard stimulus set used by Lindsey and Brown (2002). In a separate set of conditions, we tested color naming in the same groups, but using stimuli that simulated the effects of ocular media present in the complementary age group (i.e., younger observers viewed stimuli filtered through the simulated ocular media of older observers and older observers viewed stimuli filtered through the simulated ocular media of younger observers).

If the Lindsey and Brown (2002) proposal is correct, color naming by older observers in the standard condition should be similar to color naming by younger observers in the simulated aging condition. Also, color naming by younger observers in the standard condition should be similar to color naming by older observers in the simulated youthening condition. Specifically, stimuli denoted in the Munsell color system as “blue-green” and “blue” should be identified with the color name “green” more often by older subjects viewing standard stimuli and younger subjects viewing simulated aging stimuli than by younger subjects viewing standard stimuli and older subjects in the simulated youthening condition. Additionally, in the standard stimulus conditions, there should be a strong negative correlation between ocular media OD and use of the color term “blue.”

Evidence from aging studies of unique hue loci (Schefrin & Werner, 1990), hue scaling (Schefrin & Werner, 1993), and color naming in Japanese (Okajima, Yamashita, Takamura, Watanabe, & Tsuchiya, 2002), however, cast doubt on Lindsey and Brown’s predictions. These studies show that older observers tend to use linguistic color descriptors in much the same way as younger observers. This is despite their increased ocular media OD and suggests that the color naming of older individuals should be similar to that of younger observers when presented with the same stimuli.

Methods

Observers

All observers were born in the United States and were native English speakers. Observers were provided complete ophthalmic and optometric examinations prior to inclusion in this study. Only visually healthy (e.g., absence of clinically significant cataracts or retinal disorders) observers were considered for this experiment. No observers had a history of cataract surgery, and thus, all observers had intact crystalline lenses. This study included 20 observers in two age groups. There were 10 observers in the younger group (mean = 23.2 years of age, range = 18-29) and 10 in the older group (mean = 73.9 years of age, range = 68-79). The ratio of males to females in both groups was 1:1. Written informed consent was obtained before testing, based upon a protocol approved by the Office of Human Research Protection of the University of California, Davis, School of Medicine.

Ocular Media Measurement

Prior to participating in the color-naming portion of this experiment, we determined the ocular media OD for one eye of each individual. Ocular media OD was estimated for each observer based upon their scotopic (low light level) spectral sensitivity, using a variation of a technique described by Norren and Vos (1974). The rationale for this method is that under scotopic conditions, relative spectral sensitivity is dependent upon the shape of the rhodopsin (rod photopigment) absorption spectrum and the ocular media OD spectrum. The absorption spectrum of rhodopsin is essentially invariant between individuals. Thus, any differences between observers in relative sensitivity to various wavelengths of light under scotopic conditions are due to ocular media OD differences. Differences in sensitivity between individual observers and the *Commission Internationale de l'Eclairage* (CIE) standard observer for scotopic spectral sensitivity (V_) were fitted with varying amounts of ocular media OD in proportions prescribed by the lens-aging model of Pokorny, et al. (1987). The function that provided the best least-squares fit to these data was taken as the individual's ocular media OD (see Figure 1).

To measure the scotopic spectral sensitivity function, we used a Maxwellian-view optical system that permitted monochromatic light (7 wavelengths from 410 – 600 nm) to be imaged on the retina as an annulus (7-15°, inner and outer diameters) flickering as a 3 Hz square wave at 100% modulation. The observer's task was to adjust stimulus intensity by varying a neutral density wedge with a potentiometer until the stimulus was just detected. Following 30 minutes of dark adaptation, and a minimum of three practice trials, observers made a series of three threshold settings for each wavelength, presented in random order. Sensitivity was defined by the reciprocal of the energy at the geometric mean setting.

Color-Naming Experiment

In the standard stimulus conditions, stimuli were colorimetrically-simulated versions of the 40 Value-6 Munsell chips used in the 1997 World Color Survey (Kay, Berlin, Maffi, & Merrifield, 1997) presented on a CRT. The chromaticities used were from Newhall, Nickerson, and Judd (1943) who made colorimetric measurements of these chips under CIE Illuminant C. In the simulated aging and simulated youthening conditions, these stimuli were adjusted to simulate the effects of the ocular media OD of an average observer in the complementary age group. In the simulated aging conditions, the younger individual's ocular media OD was subtracted from the OD for an average 75-year-old observer (values taken from the Pokorny, et al., 1987, model for that age). This difference in OD was then subtracted, wavelength-by-wavelength, from the $\log_{10}$ of the energy spectra emitted by the CRT phosphors for the simulated chip, which was measured with a spectroradiometer (Spectra-Prichard PR703A) for each stimulus from the standard condition. The resulting function represents the light that would be necessary to present to younger observers on the CRT to produce the same retinal stimulation that the older observer would receive from the standard stimulus. The chromaticity of this spectral distribution was calculated, and the proportions of the three phosphor types necessary to produce this chromaticity were computed. This stimulus set will be referred to as the simulated aging condition. These stimuli are analogous to the simulation performed by Lindsey and Brown (2002), with the exception that we measured the OD of each individual's ocular media while Lindsey and Brown (2002) used standard values. The simulated youthening stimuli were prepared in a complementary fashion. Standard stimuli were adjusted for older observers, based on their measured ocular media OD, to recreate the retinal stimulation of an observer with the ocular media OD of the average 25 year old from the Pokorny, et al. (1987) model.

The color-naming stimuli were presented in circular (4.4^o visual angle) test patches surrounded by a uniform gray field (28.7^o x 21.5^o) on a Sony G-200 CRT. The chromaticity of the surround was (0.310, 0.316) in CIE 1931 chromaticity coordinates, equivalent to CIE illuminant C. The luminance of the background was 10 cd/m^2 for the standard stimuli. Test patch luminance was set to twice the surround for the standard stimulus conditions. In the simulated aging and youthening conditions, the actual luminance values of the test patch and surround depended on the measured values of ocular media OD. Stimuli were presented in a darkened laboratory at a viewing distance of 63.5 cm. All observers were properly refracted for the test distance using trial lenses. Stimuli were presented monocularly to the eye that was measured for ocular media OD. Each observer participated in two conditions: the standard condition and a simulated aging or youthening condition. In each condition, 40 stimuli were presented four times over the course of two sessions. Each observer began with one practice session.

Stimulus presentation was preceded by 10 minutes of dark adaptation. This was followed by 3 minutes of light adaptation to the mean background color for the condition to be tested. On each trial the simulated Munsell chip was presented for 1 sec. Following stimulus presentation, observers chose a single color name using a computer mouse, from a provided list of the 11 English BCTs (red, orange, yellow, green, blue, purple, white, black, brown, grey, and pink).

RESULTS

Figure 2 displays the color names chosen most often for each of the 40 simulated Munsell chips for younger and older observers in the standard and simulated aging and youthening conditions. The results of the simulated aging condition replicate Lindsey and Brown's (2002) major experimental findings. Observers in the simulated aging condition used the term "green" for two chips in the blue-green category of the Munsell designation that were named "blue" most often in the standard condition. In addition, chips consistently named "purple" in the standard conditions were named "pink" more frequently in the simulated aging condition. The simulated youthening condition is also consistent with the results and analysis of Lindsey and Brown (2002). There was a shift under these conditions toward using "blue" more often when naming chips in the blue-green Munsell designation that were named "green" most often in the standard condition. Older observers called one chip "yellow" in this condition that was called "orange" in the standard condition. There was also a tendency for these observers to use “purple” for some chips in the simulation that were named “pink” in the standard.

While the results from our aging and youthening simulations replicated Lindsey and Brown’s (2002) major findings, the comparison of the results from the older and younger observers in the standard condition contradicted their lens-brunescence hypothesis. According to this hypothesis, the older observers’ color-naming responses under standard conditions should be more similar to the younger observers’ responses from simulated aging than from the standard condition. Most importantly, in the standard condition, older observers should use “green” for some stimuli designated “blue” by younger observers, just as is seen in simulated aging. However, when older and younger observers were presented physically-identical stimuli, color-naming responses were very similar. Figure 3 shows the proportion of “green” and “blue” responses for the green-yellow, green, blue-green, blue and purple-blue Munsell colors. The upper panel compares older (solid lines) and younger (dashed lines) observers from the standard stimulus condition. Clearly, there is little difference between younger and older observer’s responses for these stimuli, especially in the blue-green region. For the stimuli represented in Figure 3, the response proportions for older and younger observers in the standard condition are highly correlated for both “green” ($R^2 = 0.95$) and “blue” ($R^2 = 0.99$). The lower panel compares the results of the older observers from the standard condition (solid lines – same data as above) and young observers from the simulated aging condition (dashed lines). Younger subjects in the simulated aging condition used “green” most often for several stimuli that older subjects called “blue.” Correlations for color-name proportions for simulated aging and older observers in the standard condition were lower than what was observed when both groups received the same physical stimuli (R^2 for "green" = 0.80 and R^2 for "blue" = 0.81).

The lens brunescence hypothesis predicts a strong negative relation between use of the term "blue" and ocular media OD for the stimuli tested in this experiment. This prediction is evident in a comparison of younger subjects in the standard and simulated aging conditions. Younger subjects used the term "blue" significantly more often as a proportion of total responses in the standard condition than in the simulated aging condition ($p<0.05$, two-tailed t-test). There was no significant difference between the proportion of total responses for "blue" for older and younger subjects in the standard conditions ($p=0.49$). Figure 4 shows the proportion of all trials in the standard condition in which the observer selected the color term "blue" to describe the stimulus as a function of ocular media OD of each observer at 400 nm. The regression is not significant. The slope of the regression line is -0.001 ($R^2 = 0.009$, $p = 0.89$). We cannot reject the null hypothesis that there is no relation between ocular media OD and use of the color term "blue" in normal aging.

DISCUSSION

Lindsey and Brown (2002) highlight the interesting correlation between high-UV-B exposure and the absence of a verbal distinction between the color terms "blue" and "green." This is particularly interesting as high-UV-B exposure is also correlated with accelerated lens brunescence (Werner, Peterzell & Scheetz 1990; Young, 1991; Javitt & Taylor, 1994). Based on these relations, they suggest a potential physiological mechanism linking these two correlations. They hypothesize that, because short wavelength light is absorbed by the crystalline lens in greater proportion with increasing UV-B exposure, people exposed to more UV-B light do not require the verbal distinction between “blue” and “green.” This model offers a potentially elegant explanation for the geographic distribution of blue-green relative to grue languages based entirely on a simple physiological process.

Our replication of Lindsey and Brown’s lens brunescence simulation confirmed their results. When younger observers were presented filtered stimuli simulating the spectral composition of light that would reach an older observer’s eye for the same stimulus, they used the color term “blue” less often and the color term “green” in its place. However, when the same physical stimuli were presented to younger and older observers, the two groups named the relevant stimuli in virtually the same way. There was no significant relation between ocular media OD and use of the color terms “blue” and “green.” This result fails to support the lens-brunescence hypothesis. We infer from our results that premature lens brunescence due to increased UV-B exposure could not serve as a causal mechanism to explain the lack of a linguistic distinction between blue and green.

The older observers in our study had ocular media absorption values that were, on average, ~1 log unit greater at 400 nm than those of the younger observers. The measured difference between the most and least dense ocular media in our study was 1.6 log units. The ocular media of the young observer with the least opaque lens and cornea transmitted 41 times more light at 400 nm than the ocular media of the older observer with the most opaque lens and cornea. Despite these large differences in the filtering of short wavelength light, younger and older observers used the terms “blue” and “green” in much the same way for physically-identical stimuli.

People differ widely in ocular media OD, both across the lifespan and among individuals of similar age. Despite these large individual differences, people within the same culture describe physically identical stimuli similarly on many measures of color appearance, including unique hue loci (Schefrin & Werner, 1990) and hue scaling (Schefrin & Werner, 1993). Additionally, differences in light-source spectral composition across viewing situations (e.g., the sun vs. a fluorescent light bulb) are such that the light reaching the retina from any given object will differ greatly from situation to situation. Despite the vastly different spectral composition of light reaching our retina across our life span and across different viewing conditions, we generally refer to a given object with a particular color term. If this were not the case, color names would not be useful linguistic tools.

For this uniformity to be possible, the visual system must compensate for changes in the spectral composition of light reaching the retina. This compensatory process is referred to as color constancy and has been the subject of systematic theoretical and experimental investigation for well over 100 years (e.g., Helmholtz, 1911; Hering, 1920). While the mechanisms underlying this process are not fully understood, chromatic adaptation and surround effects likely play critical roles (Kraft & Brainard, 1999). An individual’s entire visual world is filtered through their ocular media. The visual system is likely able to discount the ocular media spectral filtering effects due to this consistency across space and over time.

Lindsey and Brown reference an apparently competing sociolinguistic explanation for the absence of a blue/green lexical distinction in languages of these groups living in high UV-B regions (Berlin & Kay, 1969; Kay & Maffi, 1999). This argument is supported by the observation that distance from the equator, level of technology, and number of basic color terms are all positively correlated (Naroll, 1970; Hays, Margolis, Naroll, & Perkins, 1972; Ember, 1978); it holds that a driving force in increasing the number of color terms over time could be, as Lindsey and Brown acknowledge, that, "...as a culture becomes technologically more complex, speakers have more frequent need to distinguish objects by their colors" (p. 512). The reason tropical, and hence high UV-B, societies tend to be less technologically advanced and *vice versa*, although unexplained, is beside the point currently at issue. Despite Lindsey and Brown's welcome attempt to offer a physiological mechanism for the lack of a lexical blue/green distinction, other aspects of observed cross-language color naming pose a problem for this claim beyond the experimental data presented here. The most notable characteristic of the color term systems of the languages of low technology groups is not so much the lexical merger of green and blue *per se,* as it is the merger of several specific pairs and triples of basic colors into single terms (Kay & Maffi, 1999). For example, while the inclusion of red and yellow in a single term is less frequent than the inclusion of green and blue, languages that contain this merger are similarly distributed across the globe (see Lindsey and Brown, 2002, Figure 2). Such an inclusion could not be explained by increased lens brunescence, since the wavelengths critical for this distinction pass through the ocular media virtually unfiltered. A model of color-name evolution must account not only for the geographical distribution of languages that lack distinct terms for blue and green, but also for the distribution of languages that lack other lexical distinctions, notably the red/yellow distinction. The correlation between UV-B radiation and the absence of terms meaning blue is likely not caused by accelerated brunescence of the ocular lens, but is likely related to some additional third factor that is correlated with both phenomena.

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FIGURE LEGENDS

Figure 1. Scotopic sensitivity functions for 27 year-old (upper left panel) and 73 year-old (upper right panel) observers. Solid curves are the CIE's standard observer scotopic sensitivity function (V_), while the dashed curves are scotopic sensitivity functions adjusted for ocular media OD based on the Pokorny, et al. (1987) model. The lower panels show the estimated ocular media OD functions for the two subjects based on the scotopic sensitivity functions above.

Figure 2. Modal color names for the 40 Value-6 Munsell hues used in the World Color Survey. Box color corresponds to the color name given to that stimulus most often. The dark colored boxes reflect ≥ 80% agreement amongst observer responses. The light colored boxes reflect < 80% agreement amongst observer responses. Letters across the top correspond to the nominal colors of the simulated Munsell chips. Rows A and B illustrate modal responses in the standard stimulus condition, for older and younger groups, respectively. Row C shows observer modal responses from the older group for the simulated youthening condition. Row D shows observer modal responses from the younger group for the simulated aging condition.

Figure 3. Proportion responses for "green" and "blue" as a function of Munsell hue stimulus. Gray and black curves and symbols denote "green" and "blue" responses, respectively. The upper panel plots data from the standard stimulus conditions for older (filled symbols and solid lines) and younger (open symbols and dashed lines) observers. The lower panel plots data from older observers in the standard stimulus condition (filled

symbols and solid lines; same as upper panel) and younger subjects in the simulated aging condition (open symbols and dashed lines). Letters across the bottom correspond to the nominal colors of the simulated Munsell chips.

Figure 4. The proportion of the trials on which an individual used the color name “blue” a function of ocular media OD at 400 nm.

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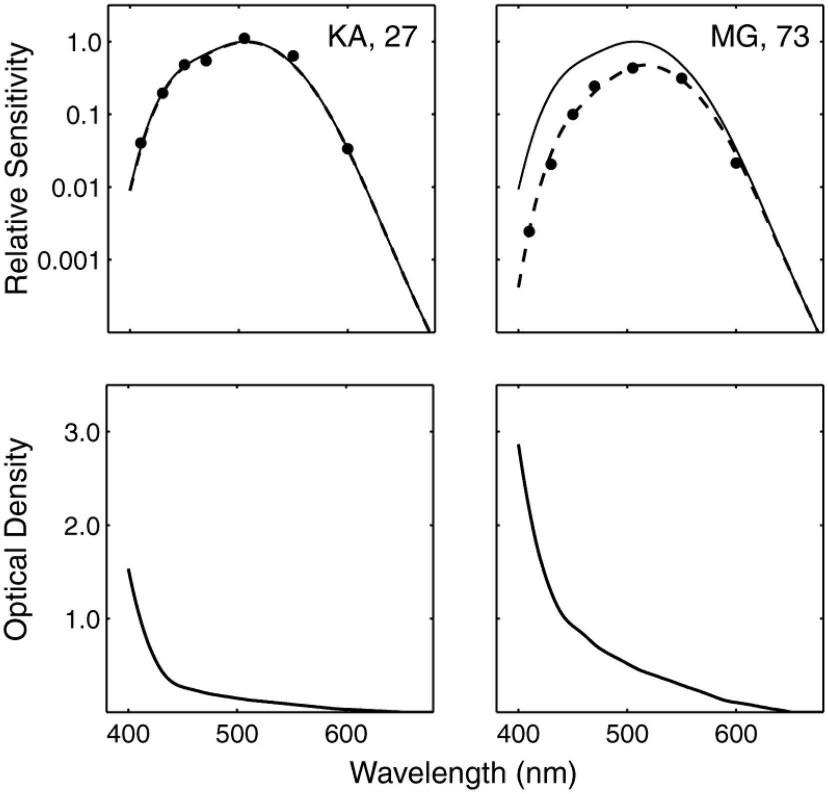
KA, 27
MG, 73
Relative Sensitivity
1.0
0.1
0.01
0.001
Optical Density
3.0
2.0
1.0
400
500
600
Wavelength (nm)

Figure 1.

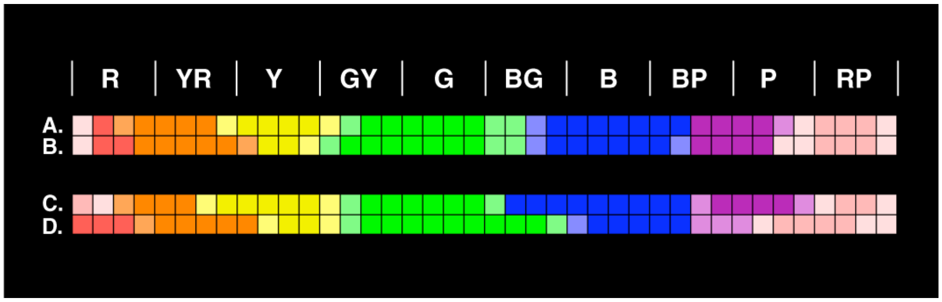

Figure 2.

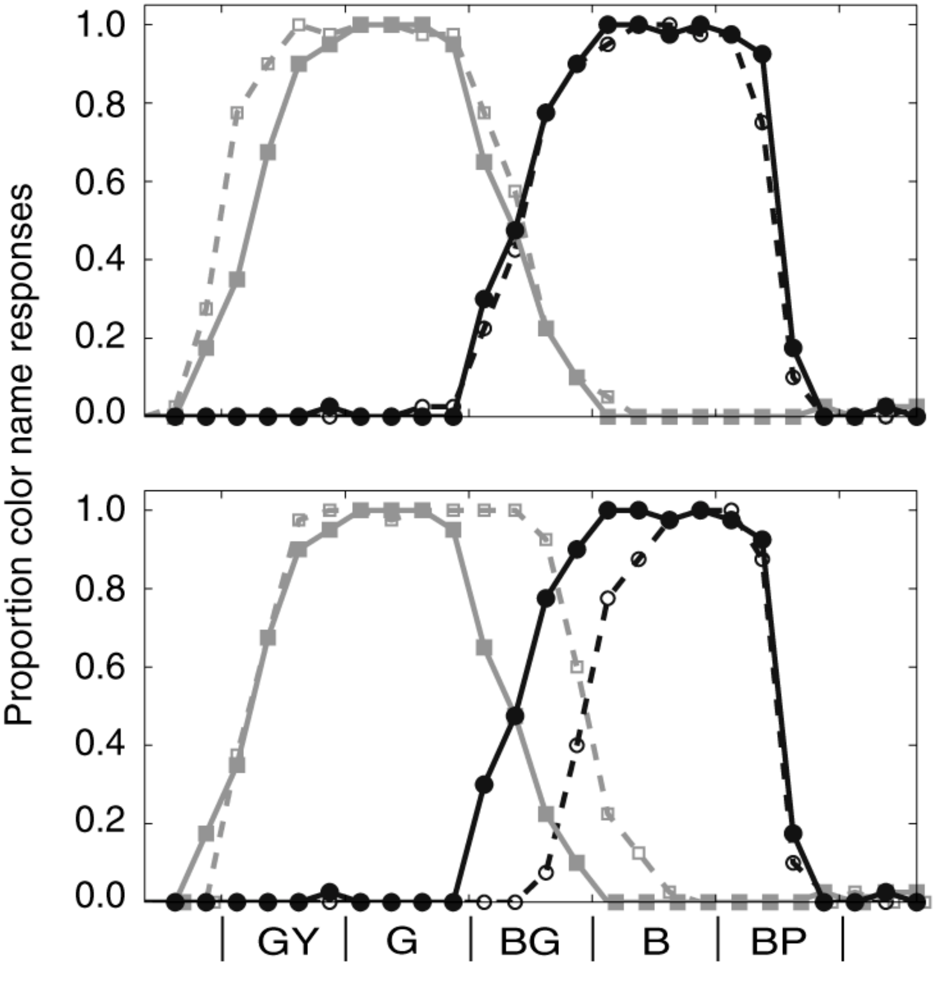

Figure 3.

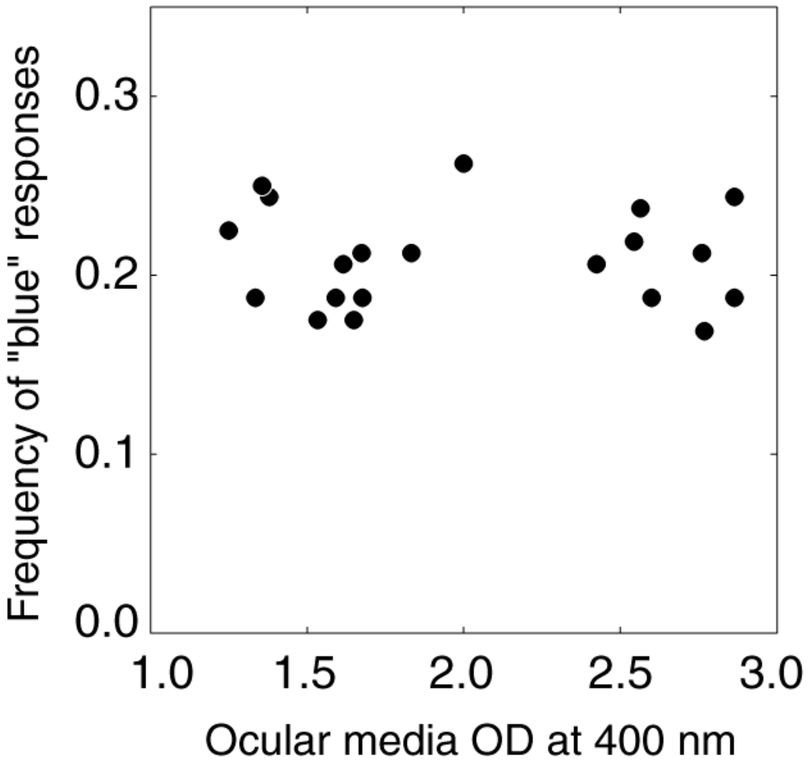
Frequency of "blue" responses
0.0
0.1
0.2
0.3
1.0
1.5
2.0
2.5
3.0
Ocular media OD at 400 nm

Figure 4.