Research Article

COLOR NAMING AND THE PHOTOTOXIC EFFECTS OF SUNLIGHT ON THE EYE

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Abstract—*Many languages have no basic color term for "blue." Instead, they call short-wavelength stimuli "green" or "dark." We show that this cultural, linguistic phenomenon could result from accelerated aging of the eye because of high, chronic exposure to ultraviolet-B (UV-B) in sunlight (e.g., phototoxic lens brunescence). Reviewing 203 world languages, we found a significant relationship between UV dosage and color naming: In low-UV localities, languages generally have the word "blue"; in high-UV areas, languages without "blue" prevail. Furthermore, speakers of these non-"blue" languages often show blue-yellow color vision deficiency. We tested our phototoxicity hypothesis in a color-naming experiment, using computerized, colorimetric simulations of Munsell colors as viewed through clear and brunescent lenses. As predicted, our young subjects used "blue" as in English when the simulated lens was clear, but named colors as in tropical languages when the lens was dense. Our within-subjects design precludes a cultural explanation for this result.*

Colors are one of the most compelling aspects of the visual environment, and most languages include distinct names for them. However, languages differ greatly in the way in which the gamut of colors is partitioned into lexical categories, such as "red," "green," and "blue" in English[1] (Fig. 1a). We have been particularly interested in the lexical status of colors that are called "blue" and "green" in American English, and that occupy distinct, adjacent regions when test stimuli are plotted in the CIE (Commission Internationale de l'Éclairage) chromaticity diagram (Wyszecki & Stiles, 1982). On the one hand, most Indo-European languages distinguish "blue" from "green" and "black"; so do languages in many other unrelated language families. We refer to languages with this property as "blue/green" languages. On the other hand, the speakers of many languages do not distinguish between "blue" and "green." Instead, they use a single color term (known as "grue" among investigators) to name stimuli with dominant wavelengths in the middle- and short-wavelength regions of the spectrum (we call those languages "grue" languages; Fig. 1b). Furthermore, in some languages, the terms for "blue" and "dark" are the same (we call them "dark" languages; Figs. 1c and 1d). Why is this so?

Despite 125 years of study (Geiger, 1871/1880; Gladstone, 1877; Rivers, 1901; Berlin & Kay, 1969/1991), in three different scholarly traditions, no one has offered an entirely satisfactory account of the diversity across languages in the color names used for short-wavelength stimuli. In the early part of the 20th century, Edward Sapir and Benjamin Whorf established one tradition, linguistic relativity, which holds that people who speak different languages perceive colors differently because of the languages they speak. That is, according to this view, language determines thought and, therefore, perception (Saunders & van Brakel, 1997).

Experimental studies consistent with this view show that at least some judgments of differences in color are related to the basic color terms available in a subject's language (Davidoff, Davies, & Roberson, 1999b; Kay & Kempton, 1984; Roberson, Davies, & Davidoff, 2000). A shortcoming of the Sapir-Whorf hypothesis is that it does not explain how the linguistic categories came to be. Furthermore, it was formulated to explain cognitive and perceptual differences, not similarities, and the available color-naming data show patterns of color naming of short-wavelength stimuli with surprisingly little cross-cultural variability, other than the "grue" or "dark" versus "blue/green" patterns we have noted.

The second tradition (Berlin & Kay, 1969/1991) emphasizes regularities in color names across cultures. According to this universalist view, languages evolve, first by partitioning colors into only two categories, "dark" and "light," and then by adding new color words in a fixed order from a universal set of 11 basic color terms that denote innate perceptual categories; the distinction between "blue" and "green" and "dark" is the last major event in this process (Kay & Maffi, 2000). But the universalist tradition fails to answer the question it poses: Why are those particular 11 categories used, and not a different set, perhaps containing many more or many fewer basic color terms? And why are the terms added in the observed order, and not some other order, or even no fixed order at all? Several investigators (e.g., MacLaury, 1997) have posited remarkably complex cognitive processes to explain these regularities. None adequately accounts for the general absence of lexical distinctions between "blue" and "green" seen in so many languages.

The third tradition, which is probably consistent with both of the previous explanations, was first advanced by Gladstone (1877) and Rivers (1901). It holds that some of the differences among languages in their color lexicons may be related to physiological and, hence, perceptual differences among the people who speak them. Accordingly, cross-cultural regularities in the use of "grue" and "dark" might have emerged because of variations across peoples in their sensitivity to short-wavelength light. Early speculation drew a parallel between the global distribution of "grue" and the dark skin pigmentation of equatorial peoples. The idea was that the same mechanism responsible for plentiful melanin in the skin might also have produced increased pigmentation of the ocular media, particularly of the *macula lutea*, the yellowish pigment of the central part of the retina. Rivers, for example, suggested an evolutionary explanation along these lines. Subsequent studies, however, have shown that the optical density of the *macula lutea* is controlled largely by diet (Nussbaum, Pruett, & Delori, 1981), and we know of no evidence that the macular pigment is systematically denser near the equator than at higher latitudes. Furthermore, differences between subjects in optical density of macular pigment are modest, and may be too small to account for the differences in perception that the color-naming data suggest (Ratliff, 1976). Thus, the macular-pigment explanation does not hold up very well, and the idea of a physiological explanation for the evolution of "grue" languages has not been pursued very vigorously in recent years.

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1. Color names appear in quotes, and may refer to the names in any language. Color names cited from other authors are glossed as in the original publication.
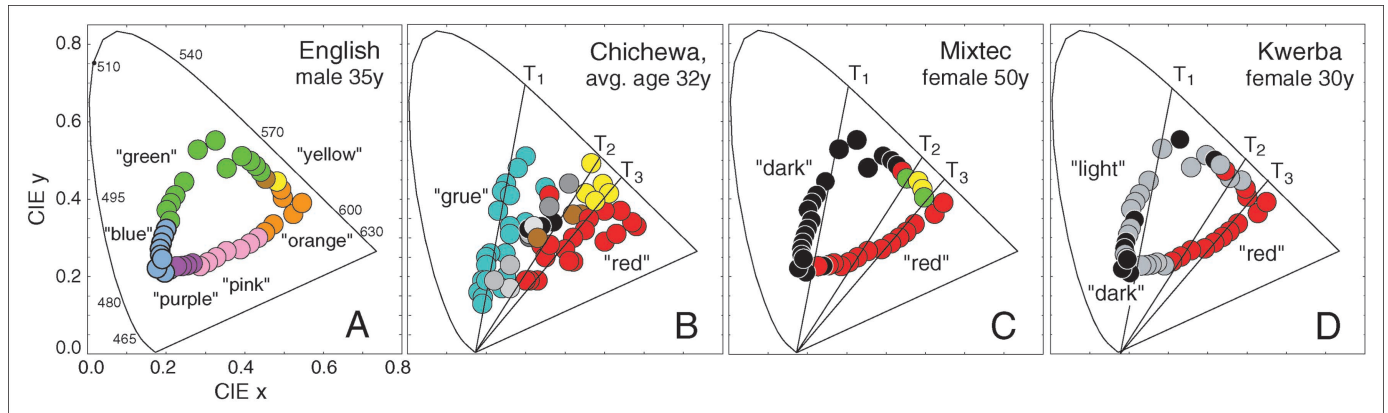
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Fig. 1. Examples of typical color-naming patterns in four languages: (a) a "blue/green" language (English, an Indo-European language; MacLaury, 1997), (b) a "grue" language (Chichewa, spoken in Malawi, southern Africa; Davies, Corbett, Mtenje, & Snowden, 1995), and (c, d) two "dark" languages (Mixtec, spoken in Mexico, and Kwerba, spoken in Irian Jaya, Indonesia; MacLaury, 1997). Data are plotted in CIE 1931 coordinates. T_1 through T_3 are tritan confusion lines. A subject with a severe short-wave cone loss (a tritanope) confuses all colors falling on each of these confusion lines. Speakers whose data are shown in (b) and (c) are not tritanopes, because names along T_2 differ ("yellow" or "green" near the top vs. "gray" or "red" further down). The speaker whose data are shown in (d), however, may be a tritanope, because the colors along T_1, T_2, and T_3 have similar names ("dark" or "light" for T_1 and "red" for T_3, with a transition zone near T_2). Coordinates for World Color Survey Value-6 Munsell samples (panels a, c, and d) were obtained from Newhall, Nickerson, and Judd (1943).

THE LENS-BRUNESCENCE HYPOTHESIS

In this article, we revisit the question of whether there is a physiological basis for the difference between languages that distinguish "blue" from "green" and the languages that merge those colors into "grue" or "dark." We evaluate the hypothesis that these differences in color naming are due to regional variations in the rate of aging of the ocular lens. Yellow pigments normally accumulate throughout the lens as it ages, preferentially absorbing short-wavelength light, and causing brunescence of the lens. Abnormally high optical density of the ocular lens is a well-known phototoxic effect of sunlight rich in ultraviolet-B (UV-B), and it is well established that high exposure to UV-B (280 nm < λ < 315 nm) accelerates aging of the lens (Javitt & Taylor, 1994). We propose that cross-cultural differences in the optical density of the lens arise from geographical variations in exposure to solar UV-B radiation. Thus, the mechanism by which the ocular media become yellow under this hypothesis is quite different from the evolutionary explanation suggested by Rivers (1901): The yellowing of the lens takes place within the lifetime of the individual speaker of a language, rather than being inherited across generations.

As the lens becomes denser, two effects on color perception are predicted. First, less light will reach the retina from spectrally narrowband, short-wavelength stimuli. Therefore, narrowband, short-wavelength stimuli would tend to be called "dark" rather than "blue." Second, the short-wavelength components of broadband bluish light will be selectively absorbed. Therefore, broadband stimuli that look pale blue, bluish, cyan, or turquoise to the normal European observer would look greenish through a dense lens. Few stimuli would look predominantly blue.

THE GEOGRAPHICAL DISTRIBUTION OF "BLUE/GREEN," "GRUE," AND "DARK" LANGUAGES

Figure 2, based on a corpus of 203 languages that we have assembled from various published sources (Berlin & Kay, 1969/1991; Bornstein,

1973; Davidoff et al., 1999b; Davies & Corbett, 1994; Davies, Corbett, & Margalef, 1995; Davies, Corbett, Mtenje, & Snowden, 1995; Davies et al., 1992; Landar, Ervin, & Horowitz, 1960; MacLaury, 1997), shows that the worldwide distribution of "grue" or "dark" languages versus "blue/green" languages is consistent with the ocular-lens hypothesis. As Bornstein (1973) pointed out previously, there is a tendency for "grue" and "dark" languages to be spoken near the equator, and "blue/green" languages to be spoken at higher latitudes. This analysis is consistent with the notion that there is a geographical basis for the use of "blue," but does not by itself say why "blue" should occur. Comparing the language data with satellite data, we found that people living where UV-B exposure is high tend to speak languages that do not have a separate "blue" category; conversely, people living where UV-B is low tend to speak languages that do (Fig. 2, inset). Admittedly, there is considerable overlap in the geographic ranges of the different language types, and our corpus of languages amounts to only about 2.5% of the languages currently spoken. Also, our corpus may not be an unbiased sample of world languages: Endangered languages or languages spoken by members of traditional cultures may be overrepresented. However, the complementary distribution of UV-B insolation and the distribution of languages having a distinct word for "blue" is statistically highly significant (likelihood ratio = 27, $df = 6$, $p = .0001$, on a log-linear test for statistical independence), and supports our hypothesis.

THE EXPERIMENT

One might think that field studies involving speakers of "grue" and "dark" languages would be required to find out whether the lens-density hypothesis has merit. We agree that such studies will ultimately be important, but we have taken a different tack here. We report a laboratory study of young, modern, color-normal, culturally homogeneous American English-speaking subjects, in which we manipulated virtual-reality colored stimuli in ways consistent with progressive brunescence of the ocular
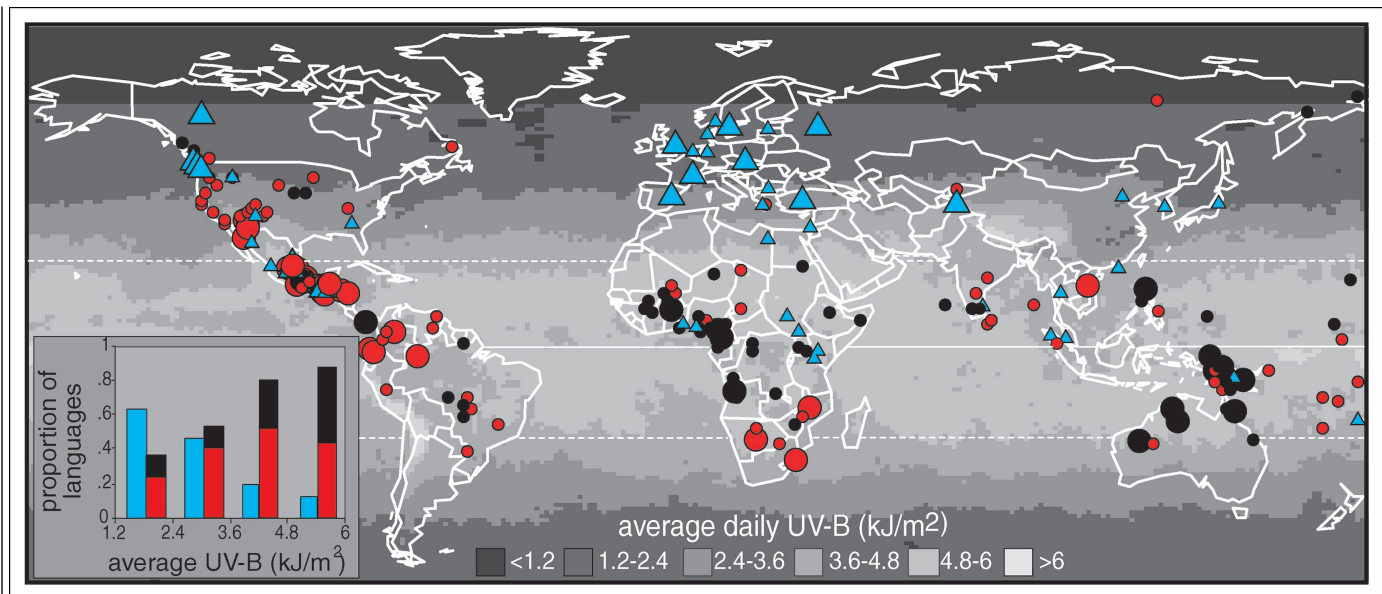
Fig. 2. Geographic locations of languages in our corpus. Languages with a distinct word for blue are indicated by blue triangles, "grue" languages are indicated by red disks, and "dark" languages are indicated by black disks. Classifications based on names given to Munsell or Color-Aid stimuli in psychophysical studies are shown by large symbols, and classifications based on lexical descriptions are shown by small symbols. The gray tones in the map background indicate ranges of annual ultraviolet-B (UV-B) insolation. The continuous horizontal line marks the equator; the dashed horizontal lines mark the Tropics of Cancer (23.5° N) and Capricorn (23.5° S). The inset shows the fractions of occurrences of languages with (blue bars) and without a distinct word for "blue" (stacked red and black bars, indicating "grue" and "dark" languages, respectively) as a function of average daily UV-B. The UV-B averages are for the year 1999, and were obtained from the TOMS Erythemal UV Exposure Web site: http://toms.gsfc.nasa.gov/ery_uv/euv.html.

lens, as might occur as a result of chronic exposure to high levels of UV-B. Our subjects knew all 11 basic color terms in English from a young age, so any experimental effects would not be due to lack of adequate vocabulary or to other possible effects of linguistic relativity. This strategy allowed us to address the following two questions: Will alteration in the proximal stimulus due to brunescence of the lens produce the patterns of color naming observed in the ethnographic studies of "grue" and "dark" languages? If so, are the lens optical densities necessary for these changes physiologically plausible?

Method

To address these two questions, we used a carefully calibrated RGB video monitor to reproduce a subset of the color samples used in the World Color Survey (hereafter, WCS; Kay, Berlin, Maffi, & Merrifield, 1997). We simulated the effects of UV-B-accelerated lens aging, and collected color-naming data from a group of 15 subjects. The subjects were color-normal, experimentally naive, native speakers of American English, aged 16 to 27 years, and gave written, informed consent before testing began.

Procedure

In a darkened laboratory, we presented 2.5° color samples, which simulated colorimetrically the 40 Value-6 Munsell chips from the WCS. The samples were surrounded by a uniform gray field (Fig. 3a) or a Mondrian (McCann, McKee, & Taylor, 1976) collage of random patches of color (Fig. 3b), also derived from the 40 Value-6 chips.

Both surrounding fields were nominally half as bright as the test sample (the exact luminance relation depended on the simulated lens condition). The computer presented the stimuli one at a time, and for each stimulus the subject chose a single color name from a menu of 11 basic color terms in English.

The experiment was blocked by simulated lens optical density. A block began with 3 min of practice trials for chromatic adaptation to the appropriate lens value. During the test phase, each of the 40 virtual Munsell color samples was presented twice, once with the gray background and once with the Mondrian background; the order of presentation of all test trials within a block was randomized. Pilot experiments were run on the authors (native speakers of American English, ages 50 and 51 years) to evaluate the adequacy of the 3-min adaptation period, which we chose on the basis of prior research by others (Fairchild & Lennie, 1992; Fairchild & Reniff, 1995; Rinner & Gegenfurtner, 2000). Two days of wearing orange spectacle lenses did not alter color naming afterward, and timed color naming during the adaptation period showed no measurable change in color appearance occurring beyond that observed after 1 or 2 min of chromatic adaptation.

Stimulus chromaticity

We simulated six different lens optical densities, spanning 1.6 to 3.3 at 400 nm (nominal European lens ages of 25 to 100 years). The maximum density of 3.3 is within the range of maximum estimates from the experimental literature on elderly subjects of European extraction (Werner, 1982). We used the lens spectral transmittance curves from Pokorny, Smith, and Lutze's (1987) model of lens aging in European sub-
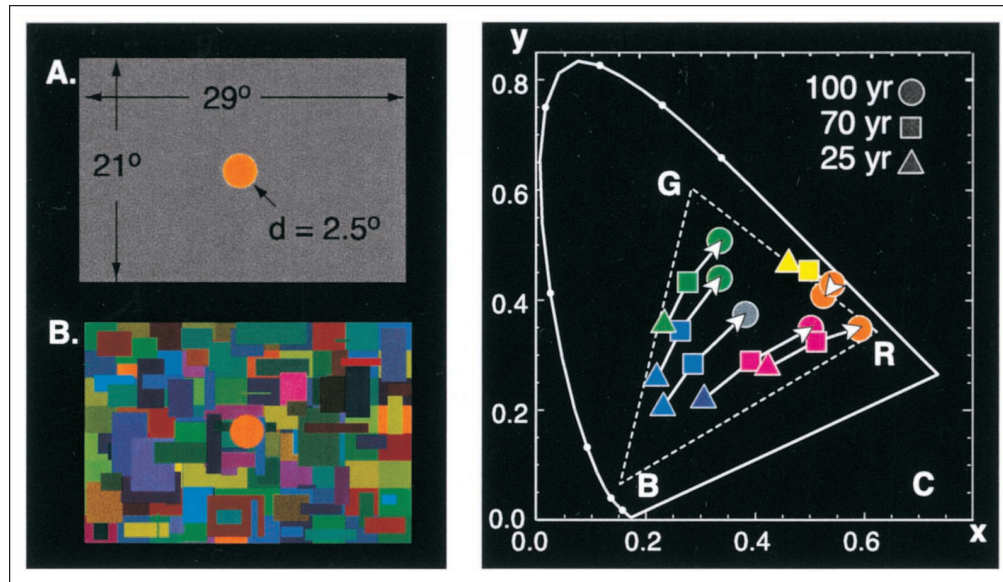
Fig. 3. Stimulus configuration with the gray (a) and Mondrian (b) backgrounds and CIE diagram (c) showing changes in chromaticity (arrows) of representative virtual-reality stimuli, as lens pigmentation increases with nominal European lens age. The colors shown indicate modal color names in our study. Notice that the two "blue" chips become "green" and "gray," respectively, at nominal age 100. The purple chip becomes pink by nominal age 70. The dashed line shows the color gamut of the computer display; R, G, and B are chromaticities of the red, green, and blue phosphor primaries, respectively. All displayable chromaticities fall inside the RGB triangle. Note that some computed colors fall above the (R, G) gamut boundary. In these cases, chromaticity coordinates of actual stimuli were projected onto the R, G mixture line.

jects, and the chromaticities of the 40 color samples and their surrounding fields viewed under Standard Illuminant C were from Newhall, Nickerson, and Judd (1943). We adjusted the stimuli by multiplying the RGB phosphor spectra by the spectral transmittance curves to reproduce the color samples as they would appear if viewed through each of the six different lenses (Fig. 3c). A few of the yellow stimuli were desaturated slightly from their calculated chromaticity to fall within our display's color gamut (Sony Multiscan 17sfII monitor; 3 guns × 8 bits/gun; 1024 × 768 pixel resolution; phosphor chromaticities: R = {0.6225, 0.3432}, G = {0.2831, 0.6037}, B = {0.1520, 0.0655}). All colorimetric calibrations were performed by a PR-703 computer-controlled spectroradiometer (PhotoResearch, Chatsworth, California; 380–700 nm in 2-nm intervals). Calibration errors were under 1%; repeatability was much better than 1%.

Results

The modal color-naming results from our study and from two other sources appear in Figure 4. When the simulated lens was young and clear, our subjects used "blue" for a wide range of stimuli, as did speakers of "blue/green" languages (compare the lower rows of our experimental results with Rows E–G). As older, yellower lenses were simulated, subjects called fewer and fewer stimuli "blue" or "purple," whereas the use of "green" increased. At the densest lens values, "blue" was replaced by "green," analogous to "grue," and to a lesser extent by "gray," analogous to "dark" (compare the upper rows of our experimental results in Fig. 4 with Rows A–C). The qualitative similarity between the color naming at the oldest, densest lens values in our experiment and color naming by the speakers of "grue" and "dark" languages is striking.

Some boundaries between color-name loci, particularly between "yellow" and "green" and between "green" and "blue," changed position along the color axis as older, denser lenses were simulated. This result leads to the interesting prediction that lexical distinctions among "grue" speakers are not merely a subset of those made by "blue/green" speakers. Rather, speakers of each language type should distinguish colors that speakers of the other language type do not. Just such a result has been reported recently in a comparison between English and the Berinmo language from Papua New Guinea (Davidoff et al., 1999b; Roberson, Davies, & Davidoff, 2000; compare Rows A–G in Fig. 4). No explanation based on linguistic relativity is needed to explain this phenomenon.

Figures 5a and 5b present the data in more detail, at maximum and minimum simulated optical density. The fraction of subjects who applied each color name to each chip in our laboratory experiment can be compared with similar field data on Navajo and English speakers (Landar et al., 1960), shown in Figures 5c and 5d. Our subjects with clear simulated lenses (Fig. 5a) and the English speakers of Landar et al. (Fig. 5c) used "green," "blue," "purple," and "red" or "pink" over relatively broad ranges, with high concordance among speakers. In contrast, our subjects at the simulated age of 100 years (Fig. 5b) and the Navajo speakers (Fig. 5d) showed poor concordance in the regions called "blue" and "purple" in Figures 5a and 5c. In both the elderly-lens and the Navajo data sets, "blue" tended to be replaced by "green" (English and Navajo) or "grue" (Navajo); also, "purple" was generally replaced by "gray" (on the border with blue) or by words that young English speakers use to denote pinkish colors. The two data sets agree qualitatively quite well, although quantitative agreement is not possible because they were collected using different Munsell stimulus sets.
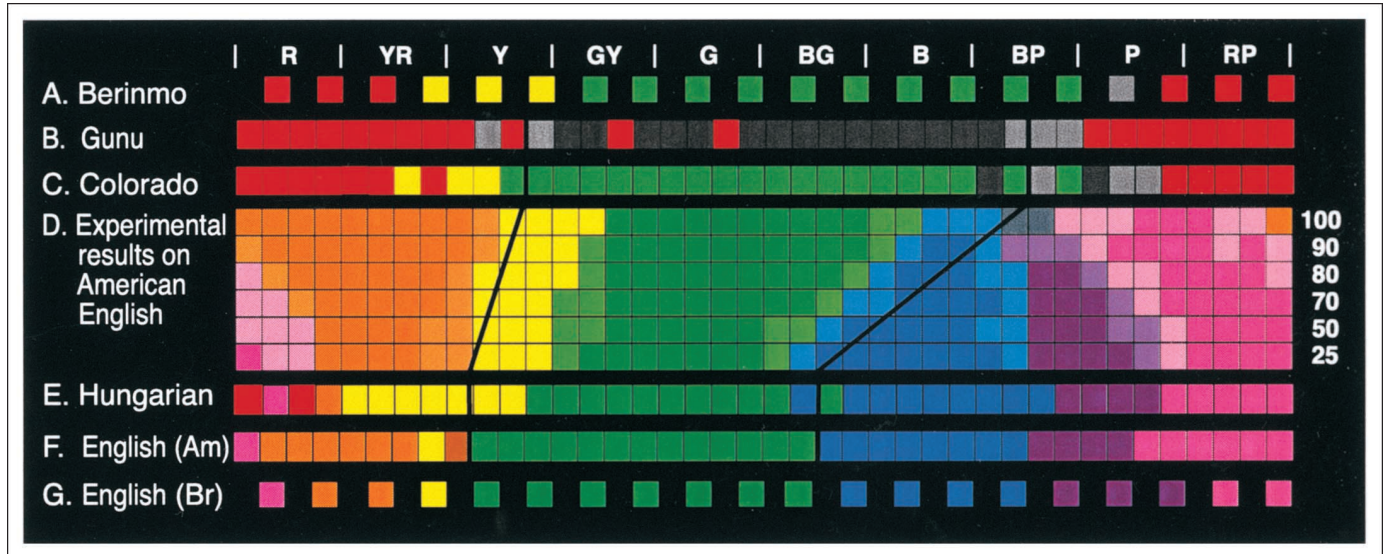
Fig. 4. Modal color names applied to 20 or 40 colors from Value 6 of the World Color Survey array. Munsell hues (R, YR, . . . , P, RP) are listed across the top. The color coding is keyed to color names in English: "red," "pink," "orange," "yellow," "green," "blue," "purple," "dark/black," "light/white," and "brown." Rows A through C show data for "grue" and "dark" languages (Davidoff, Davies, & Roberson, 1999b, for Row A; MacLaury, 1997, for Rows B and C); Row D shows modal color names used by 15 young U.S. English speakers, at simulated lens optical densities for Europeans aged 25 to 100 years (ages listed at right; desaturated colors: <80% concurrence among speakers; saturated colors: ≥80% concurrence); Rows E through G show data for "blue/green" languages (MacLaury, 1997, for Rows E and F; Davidoff et al., 1999b, for Row G). The dark diagonal lines emphasize the similarity between the shifts due to yellowing of the ocular lens and the shifts between languages.

Generality and limitations of our experimental results

These results do not necessarily account for all aspects of cultural variation in color naming in the short-wavelength region of the spectrum. For example, when color-normal speakers of "grue" languages are asked to choose the color that is the best example of "grue" (the "focal grue"), they generally choose colors that are either "focal green" or "focal blue" to speakers of "blue/green" languages, rather than the middle of their own "grue" range. Kay and McDaniel (1978) developed a theory based on fuzzy sets to account for this. We did not collect focal-color judgments from our subjects, so our results do not address this issue.

Other aspects of the generality of our results also remain to be explored. For example, we studied only one row of the WCS stimulus set in detail. Other stimuli might produce different color names in our experiment, as they do in the field. Furthermore, we know of no one, either in the field or in the laboratory, who has investigated these issues using monochromatic light. Such a project would be interesting, because a brunescent lens would reduce the retinal illuminance of a monochromatic stimulus, but would not change its relative spectral composition. Such a light, which is rare in nature and therefore might not have its own color name, should look blue if it is bright enough. Finally, our protocol does not control for the possibility that visual adaptation processes occurring over a period of years might partly cancel the perceptual effects that we observed in our simulations of lens brunescence.

Physiological plausibility of the required UV-B dosage

When the simulated lens was dense, our young American subjects named colors as though they were speaking a "grue" or "dark" language, rather than English. The lens density required to produce this behavior corresponded to that of a 90- to 100-year-old European. Is such a dense lens plausible, given that the speakers of "blue/green," "grue," and "dark" languages in the psychophysical studies in our corpus were about 45 years old, on average? We think that it is. For example, our corpus of languages includes Chichewa and Setswana, two "grue" languages spoken in southern Africa (Davies, Corbett, Mtenje, & Snowden, 1995; Davies et al., 1992). Their localities receive 3.25 times more UV-B radiation than Greenwich, England. Assuming that lens aging is linearly related to lifetime UV-B exposure, the average 30-year-old southern African could have as dense a lens as a 98-year-old Briton. The contrast would be even greater if the typical African spent more time out-of-doors than the typical Briton, a reasonable supposition, considering the weather in the two climates.

DISCUSSION

Our project has produced two results. First, we have shown that the fraction of "grue" and "dark" languages increases with annual UV-B insolation, and presumably with the lifetime cumulative ocular exposure to UV-B (Fig. 2). Second, we have shown that if young, native speakers of American English name colors through a simulated ocular lens, the color-naming data obtained through a plausibly-dense brunescent lens are similar to the data obtained from native speakers of "grue" and "dark" languages (Figs. 4 and 5). These results suggest that the occurrence of these languages near the equator has a fundamentally biological basis. Because of our within-subjects experimental design, it would be difficult to explain our results parsimoniously in solely cognitive or sociological terms.

Sunlight and Color Vision Deficiency

Short-wavelength sunlight has two phototoxic effects on color vision. One is brunescence of the ocular lens from exposure to UV-B, which
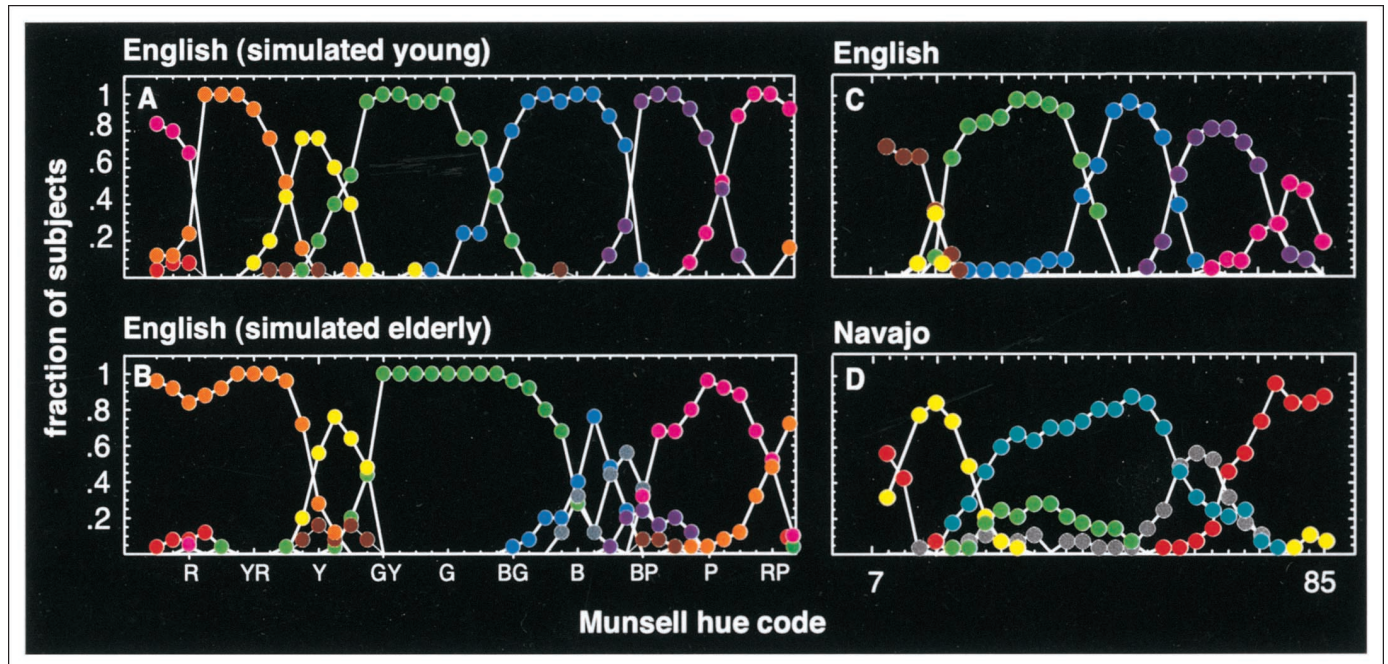
Fig. 5. Fraction of subjects applying each color name to each Munsell color sample. The colors of the symbols correspond to the basic color terms in English, except for the cyan-colored symbols in (d), which indicate the use of "grue." The panels on the left show the results of our experiment, which simulated optical densities found in Europeans aged 25 years (a) and 100 years (b). The panels on the right show results from Landar, Ervin, and Horowitz (1960), for subjects speaking English (c) and Navajo (d), tested in the field using a subset of the Munsell colors of the F-M 100-hue test (see Pokorny, Smith, Verriest, & Pinckers, 1979, for a discussion of this test).

reduces the amount of short-wavelength light arriving at the retina (Pokorny, Smith, Verriest, & Pinckers, 1979; Young, 1994). The other is direct, selective damage to the short-wavelength-sensitive (SWS) cones caused by UV and visible light (Harwerth & Sperling, 1971; Werner, Steele, & Pfoff, 1989). Both of these phototoxic effects can produce clinical blue-yellow color vision defects, but blue-yellow defects can also occur as a result of ocular pathology (see Pokorny et al., 1979). Some clinical color vision tests (e.g., the City University Test, second edition; Fletcher, 1980) can reveal blue-yellow defects, if present, but do not readily distinguish them or their causes.

Tritanopia is a dichromatic color vision deficiency that indicates a lack of SWS cone function; it can result from a genetic abnormality or from disease. Subjects with tritanopia confuse all the colors falling along each tritan confusion line (e.g., T_1, T_2, and T_3 in Fig. 1), so all the colors along any tritan confusion line share a single color name in a tritanope's vocabulary. Color-naming data suggest that some speakers of "dark" languages might have an acquired tritanopia-like color defect (Fig. 1d), perhaps concomitantly with damage to the ocular lens. However, it is unlikely that all or even many speakers of "grue" and "dark" languages are tritanopes, because most of these languages have convincingly distinct names for colors on some tritan confusion lines (notice the different color names along the T_2 confusion line in Figs. 1b and 1c).

If phototoxic effects are as widespread as the distributions of "grue" and "dark" languages suggest, then the prevalence of clinical blue-yellow color vision defects should be correlated with exposure to short-wavelength sunlight. The small amount of available data is consistent with this view. In localities where UV-B insolation is high, 5.3% to 32% of rural-dwelling subjects show blue-yellow defects on the City University Test, and the prevalence of blue-yellow defect increases with age

through adulthood (Davidoff, Davies, & Roberson, 1999a; Davies, Corbett, Mtenje, & Snowden, 1995; Davies et al., 1992; Davies, Laws, Corbett, & Jerrett, 1998). In contrast, in urban populations and among subjects who live where UV-B insolation is low, blue-yellow defects are rare (Davies et al., 1998; Ozgen & Davies, 1998; Pokorny et al., 1979).

Sociological Factors and the Establishment of Words for "Blue," "Grue," and "Dark"

Our proposal does not require that all or even most members of a society suffer from a densely brunescent ocular lens. Acquired defects are notoriously variable across individuals. We would expect some variability from person to person in lens density, even within a given locale and culture, as a result of individual differences in exposure and susceptibility to the phototoxic effects of sunlight. However, "grue" or "dark" could become established as the predominant color term for "blue," even if only a minority of the community were affected, because communication of color information requires color competence in both speakers and listeners. If the fraction of individuals in the general population who are affected is α, then only $(1 - \alpha)^2$ random dyads will involve a speaker and a listener who both have a color vocabulary that includes "blue." For example, if 10% of the population were affected, then 81% of all dyads would be able to use "blue" unambiguously; if 25% were affected, only about 55% of all dyads would. This effect would be even more pronounced for triads or larger groups of people. Thus, "grue" could become established in a language even though many members of the community retain the ability to distinguish "blue" from "green" and "dark." Consistent with this line of reasoning are published examples of color naming by multiple speakers of a given language,

which show clear individual variability (MacLaury, 1997, pp. 64–65), and even in American English there is some evidence of an association between variations in physiology and color naming (Jameson, Highnote, & Wassermen, 2001; see also Winderickx et al., 1992). Thus, the interactions among culture, physiology, and language that ultimately determine the usage of color terms are complex and remain to be explored in greater detail.

Consistency With Other Explanations

We have shown experimentally that variations in ocular lens density can affect color naming dramatically, even in a culturally and linguistically homogeneous sample of subjects. Although our color-naming results are thus explained without recourse to ideas from anthropology, cognitive science, or linguistics, they also do not challenge the importance of these other fields in understanding color categorization. For example, our results are fully consistent with the idea that the emergence of color names follows a set sequence. Berlin and Kay (1969/1991) argued that as a culture becomes technologically more complex, speakers have more frequent need to distinguish objects by their colors. We would add that the lifestyles of its people may also change: More individuals may work indoors, and learn to read, shielded from the damaging effects of the UV radiation in sunlight. The historical timing of this change may also have been correlated with climate. Thus, interactions among technology, climate, and lifestyle can account for the late occurrence of "blue" in color-naming evolution noted by Kay and Maffi (2000).

We recognize the considerable influence of unique local, cultural factors on the development of lexical distinctions of color (Pastoureau, 2000). However, we also emphasize that the evolution of basic color terms for stimuli in the short-wavelength region of the spectrum occurs apparently independently among languages that are not obviously related to one another. This suggests a universal cause, which we believe affects visual physiology in a systematic way. We have presented geophysical, psychophysical, and epidemiological evidence that yellowing of the ocular lens due to excessive exposure to UV light is just such a universal causative factor.

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