

Renormalization of Color Mechanisms Across the Life Span

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ABSTRACT

Throughout the life span, there is reduction in retinal illuminance, particularly at short wavelengths. Concurrently, there is a reduction in sensitivity of the photoreceptors and numerous morphological changes in the visual pathways. As a result, there is a great deal of age-related change in the retinal stimulus and the signals leaving the retina for perceptual analysis. Nevertheless, we have found that there is a remarkable degree of stability in color perception across the life span. Color naming of broad-band reflective samples, the wavelengths of unique blue and yellow, saturation and the achromatic locus are all relatively invariant with normal aging. Stability of color perception despite many changes in the retinal stimulus implies that the visual system continuously renormalizes itself to maintain constancy of perception. Thus, an elderly person may call the same stimulus "white" as he or she did 70 years ago, even though it must be based upon a markedly different retinal stimulus and mechanism sensitivities. To characterize the renormalization implicit in these findings, we measured the chromaticity of the achromatic point before and after cataract surgery. There was a shift following cataract surgery (removal of a brunescient lens) that was initially toward yellow in color space, but over the course of months, it drifted back in the direction of the achromatic point before surgery. This long-term renormalization is as it should be; otherwise, the white of the young would be the yellow of the old. Such adjustments may occur by calibrating the average responses in color mechanisms according to the average color in scenes (similar to the processes of von Kries adaptation) and the consequent changes in white may be particularly useful as an internal reference for color constancy.

1. INTRODUCTION

What are the consequences for the average 70-year old who, compared to the average 25 year-old, receives less than one-third the retinal illuminance due to a more dense lens and smaller pupil,¹ a substantially greater loss of S- than M- or L-cone stimulation due to the selective absorption changes in the lens,² sustains an additional factor of four loss in the sensitivity of each class of photoreceptor³ and has about 30% fewer retinal ganglion cells⁴? Most studies of aging have considered this question in relation to thresholds (see reviews by Weale⁵, 1992, Knau and Werner⁶) and discrimination,^{7,8} but have seldom considered the consequences for how subjects actually experience the world. The results of recent studies on color appearance in the elderly are surprising in that they reveal a remarkable degree of stability across the life span, as summarized in the next sections. To achieve this stability, however, raises new questions about how it may be accomplished when much of the visual system is changing. The problem is partly that of color constancy whereby the system must compensate for changing illumination, but it is more complex, for not only is the stimulus changing with age, but so too is the system used to analyze it.

2. STABILITY OF HUE PERCEPTION WITH AGING

We⁹ began by asking whether color terms were applied to natural broadband stimuli in the same manner by younger and older observers. Fifteen stimuli were selected from the Optical Society of America (OSA) Uniform Color Scales and presented as 2° test surfaces in a middle gray ganzfeld-like hemisphere with an

illuminant having a correlated color temperature of 6200 K. Scaling data were obtained using 15 younger (mean age = 21 years) and 15 older (mean age = 72 years) subjects. Five stimuli were presented at three lightness levels (in OSA space); one set was equal to the surround lightness while the other two sets of stimuli were four steps above and four steps below the surround lightness. Each lightness level included samples chosen so that one pair plotted along a tritan axis in MacLeod-Boynton receptor-excitation space¹⁰ and another pair plotted approximately on an axis of constant S-cone stimulation. The chromatic and achromatic components were scaled for each stimulus using the 4+1 categories method.¹¹ The appearance of each test stimulus was first scaled in terms of the percentage of each fundamental hue, red, green, yellow, and blue. In a second series of trials the subjects described the proportion of overall chromatic and achromatic content.

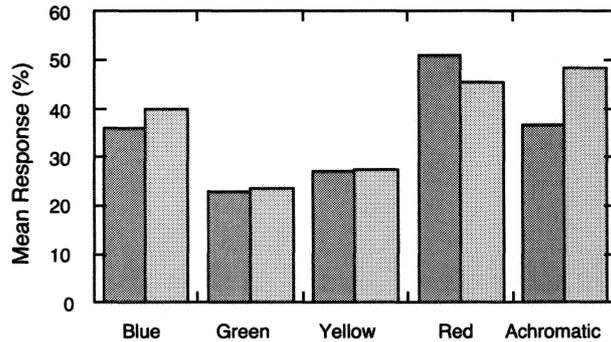


Fig. 1. Mean percentages assigned by younger (dark bars) and older (light bars) observers to 15 broadband surfaces from the OSA Uniform Color Samples. (From Scheffrin and Werner.⁹)

Color-naming percentages averaged across stimuli in which a particular hue name was assigned by either group are presented in Figure 1. Also shown by the bars on the far right are the mean achromatic (black/white) proportions for the two age groups. Not only were the same hue names assigned to the same stimuli by each group, but younger and older means did not differ by more than about 5% for each hue. Statistical analyses failed to reveal any significant overall differences between younger and older subjects' hue-naming percentages. The achromatic proportion assigned to the stimuli was, however, significantly different for younger and older observers. In general, older subjects perceived the colors of all stimuli to have more achromatic content (less chromatic content) than demonstrated by younger observers. Differences between the two age groups in perceived chromatic content of the test stimuli progressively increased as the lightness and luminance levels of the test stimuli decreased. In other words, the two groups differed primarily for darker colors. These results are similar to those reported by Okajima, Tsuchiya and Yamashita¹² using 75 chips. Essentially no difference between young and old were found when the subjects chose one of 11 color names for each stimulus. When the task involved assigning percentages to each hue term, there were small differences that depended on saturation.

Control experiments by Scheffrin and Werner⁹ with young observers were conducted using a neutral density filter and a broadband yellow filter that simulated the effects of smaller pupils in the elderly¹³ and the senescent lens,^{14,15} respectively. These tests showed that following 15 minutes of adaptation with the yellow filter, younger subjects' performance was not shifted to that of elderly subjects, perhaps implying a long-term adaptation process or senescent changes at some level of processing for the latter group.

The relative stability of hue perception across the life span is further supported by measurements of the wavelengths of the spectral unique hues. Figure 2 shows results obtained from 50 observers with 1° diameter stimuli presented at one of the three (7.1 cd·m⁻²) luminance levels tested.¹⁶ Similar results were obtained at other luminance levels for unique blue and unique yellow as well as in a separate study of 50 observers using Maxwellian-view.¹⁷ Thus, unique blue and yellow are relatively constant across luminance level and observer age. Unique green was neither constant with luminance level nor with observer age, presumably because photoreceptor signals are combined non-linearly by the yellow-blue chromatic process.^{18,19} The change in unique green with age may thus be secondary to a reduction in physical intensity of the stimuli resulting from lenticular senescence or secondary to the effective intensity of signals from aging cone photoreceptors.³

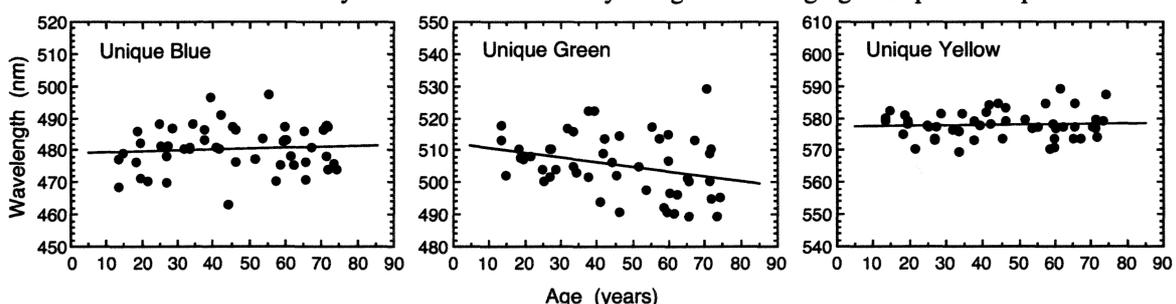


Fig. 2. Wavelengths of unique blue, green and yellow plotted as a function of age for 50 observers. Solid lines are fitted by least squares regression. (Date from Scheffrin and Werner.¹⁶)

3. STABILITY OF SPECTRAL BRIGHTNESS AND SATURATION WITH AGING

To explore whether the perception of brightness for spectral lights is predictable from age-related changes in ocular media density, Kraft and Werner²⁰ measured heterochromatic flicker-photometry and heterochromatic brightness-matching functions using a 1.2° foveally-viewed stimulus with 50 observers, ranging in age from 19 to 85 years. (See also Sagawa and Takahashi.²¹) As expected from earlier work by Verriest,²² heterochromatic flicker-photometry sensitivity was similar for all observers at long wavelengths, but decreased at shorter wavelengths with increasing observer age. These changes are consistent with age-related changes in ocular media density and show that there is no compensation or normalization of relative sensitivity for lenticular senescence in the heterochromatic flicker photometry function which is mediated by an achromatic mechanism. Indeed, this function can be used to estimate individual observer's ocular media density, if one makes reasonable assumptions about the M- and L-cone action spectra.

Heterochromatic brightness-matching sensitivity data were also similar across observers at long wavelengths, on average, but declined at short wavelengths as a function of increasing age. However, the decline in sensitivity at short wavelengths was substantially less than for the heterochromatic flicker photometry functions. By using ocular media density estimates from the heterochromatic flicker photometry functions, heterochromatic brightness-matching functions could be specified at the retina. Linear regression of brightness sensitivity at each wavelength and age, which fitted the retinally-equated heterochromatic brightness-matching functions well, were used to estimate the change in heterochromatic brightness-matching sensitivity per decade. This analysis showed that heterochromatic brightness-matching sensitivity actually *increases* as an increasing function of age, but only over the range of about 420 to 560 nm where it is needed to compensate for lenticular senescence. The average increase of ≈ 0.05 per decade implies that sensitivity at the retina would double for the average person between ages 10 and 70 years. Of course, this compensation is not spectrally perfect because the ocular media density spectrum is different from the spectral response of any single cone type or their various postreceptor combinations. As a result, the compensation in the heterochromatic brightness-matching data is too low at some wavelengths and too high at others relative to what would be needed for perfect compensation for lenticular senescence.

To determine whether similar processes influence age-related changes in saturation scaling, we measured colorimetric purity (Pc) discrimination²³ and saturation scaling²⁴ for 21 observers ranging from 22 to 88 years (18 individuals were the same for both tasks). Test stimuli of 1.2° diameter were presented in Maxwellian view. Discrimination was measured using a temporal 2AFC procedure in which the subject was asked to signal which of two primarily broadband white (CIE $x, y = 0.33, 0.35$) stimuli also contained a chromatic component derived from a superposed monochromatic light (420-680 nm). Retinal illuminances (250 td and 10 td) were equated on the basis of individual heterochromatic flicker photometry (HFP) functions. Measured Pc discrimination sensitivity was lower in the older group than in the younger group at both retinal illuminances, and the performance difference between the age groups was approximately constant across the spectrum after corrections for ocular media light losses were applied. The difference between discrimination at 10 td and 250 td was relatively small for the younger group, but larger for the older group, indicating a selective

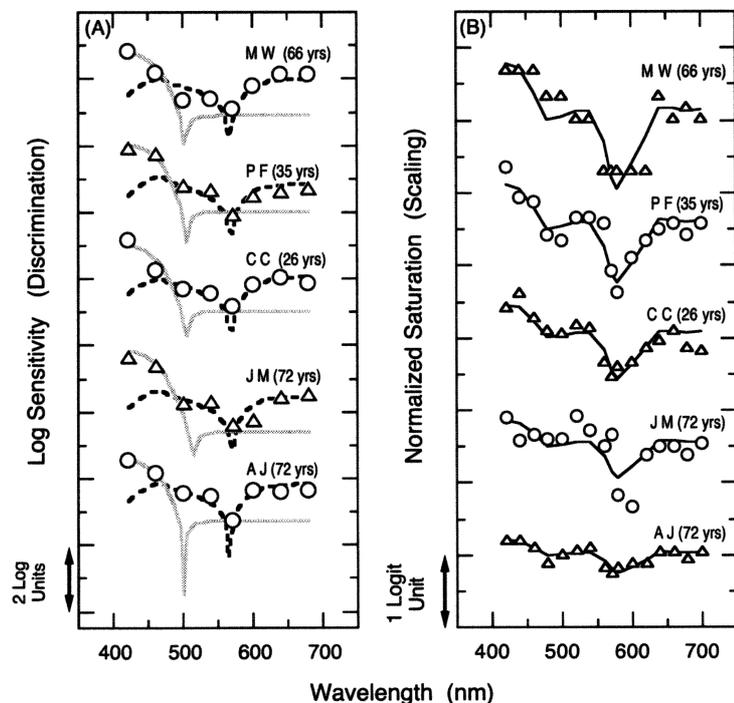


Figure 3. Panel A shows colorimetric purity discrimination functions for 5 observers plotted as a function of wavelength. The functions have been shifted arbitrarily along the ordinates, but for any one observer, higher points indicate better discrimination. The two curves show S-(L+M) (light, solid) and L-M (dark, dashed) mechanisms used to fit the data. Panel B shows scaling data, with individual subjects shifted arbitrarily along the ordinates. Smooth curves represent model fits. (From Kraft and Werner.²⁴)

performance decrement for older observers at low light levels. The data were modeled as a Euclidean sum of differential weighted responses from S-(L+M) and L-M opponent mechanisms. Figure 3A presents data from 5 observers and model fits showing the contributions of the S-(L+M) and L-M opponent mechanisms represented by the solid and dashed curves, respectively. Regression analyses using all subjects indicate similar age-related losses of sensitivity in the two chromatic mechanisms, perhaps secondary to receptor sensitivity losses.

In the main scaling experiment, two sets of stimuli were used, one equated at the cornea by a luminosity function for a standard observer and the other equated in retinal illuminance by individual HFP functions. Observers were asked to assign percentages to indicate the proportion of a desaturated stimulus that appeared chromatic. Fig. 3B shows saturation scaling data for 5 observers chosen to illustrate the variation in dynamic ranges of the functions, which are known to vary substantially between observers.²⁵ The symbols show logit-transformed saturation plotted as a function of wavelength. Comparing the corneally-equated and retinally-equated stimuli reveals that the visual system of the elderly observer can compensate for age-related changes in ocular media density over a certain range values. In other words, their scaled saturation is more similar to that of a young person despite large changes in the retinal stimulus due to lenticular senescence and losses of receptor sensitivity. There is a limit, however, as might be expected, and compensation is less complete for individuals with more extreme lens density. There is also a limit when the field sizes are small. Knau and Werner²⁶ obtained saturation scaling for 58 observers (18 to 83 years of age) using nine field sizes and three retinal locations. Older observers require larger stimuli to reach the asymptote of the function relating saturation to field size, although the critical size is still small. Overall, these and other data from our lab show that despite substantial senescent losses in sensitivity of cone mechanisms and poorer chromatic discrimination, color appearance is relatively less affected by aging.

4. STABILITY OF THE ACHROMATIC POINT WITH AGING

The previous sections described the stability of color appearance over various regions of color space, but not at its theoretical center, the achromatic or white point. This point is important in color theory because it depends on the balance of all chromatic mechanisms, and is potentially a sensitive indicator of color appearance changes with age in any direction.

Age-related shifts in the locus of the average achromatic point might be expected due to senescent changes in the ocular media, as well as changes in receptor and postreceptor processes. The arrows in Figure 4 show theoretically predicted shifts in the chromaticity of a light mixture that appears achromatic. If the intersection of all arrows represents a theoretical observer at age 10 years, it is straightforward to calculate the expected shift due to lenticular changes for an average observer at age 80. This is shown by the solid arrows, with different arrows derived from different additive mixtures of short and long-wave pairs of lights. Because age-related increases in ocular media density will cause less short-wave light to reach the retina, an older observer would be expected to compensate by adding more short-wave light in the mixture to restore the retinal stimulus to be metameric at the retina for a younger observer. As a result, aging of the lens is predicted to shift the mixture perceived as achromatic to short wavelengths as shown by the solid arrows. The dashed arrows show additional shifts if there were selective losses in S-cone sensitivity.

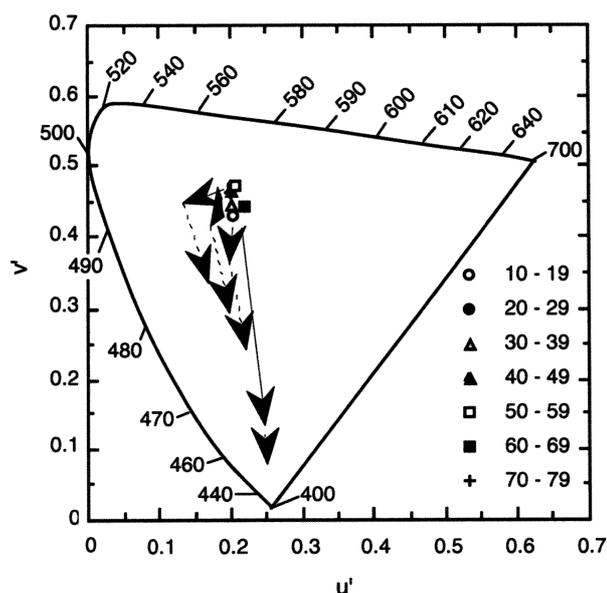


Fig. 4. The intersection of all arrows represents the location of a theoretical achromatic point for a 10-year-old observer plotted in CIE 1976 u',v' chromaticity coordinates. Arrows show the expected shift in this point resulting from changes in the ocular media from age 10 to 80. Different arrows are associated with different pairs of monochromatic lights. Dashed arrows represent additional age-related changes in the achromatic point expected from selective losses in S cones. Data points, several of which are occluded due to overlap, represent average achromatic loci of different age groups. [Data from Werner and Schefrin.¹⁷]

The data points in Figure 4 show that the predictions do not agree with the data. Each datum represents the mean chromaticity of the achromatic point for each age group. 50 observers were tested by asking them to vary the ratio of a short- and long-wave light (their unique blue and yellow for convenience) to find a balance that appeared achromatic. Contrary to expectations, there was no significant shift in the achromatic point with observer age. Because the loss in short-wave light reaching the retina is certain, a constant achromatic point with age must imply that one or more processes renormalize or recalibrate the visual system to maintain constancy across the life span. Werner and Scheffrin¹⁷ described a simple quantitative model whereby the visual system adjusts the relative response of the three classes of cone photoreceptors so that it is constant with respect to an arbitrary "white" (equal-energy was used as an example). This is reminiscent of long-term von Kries adaptation in a "gray world" and is similar to processes suggested in other contexts by Pokorny and Smith²⁷ and Mollon.²⁸ The next section describes a more direct test of the hypothesis that the stability of color perception is due to renormalization in response to age-related changes in the ocular media.

5. TESTS OF RENORMALIZATION FOLLOWING CATARACT SURGERY

The results in the previous sections are consistent with the hypothesis that the visual system renormalizes itself so that stimuli specified at the cornea appear similarly even though they change at the level of the retina over the life span. Relevant direct tests of this idea are lacking as most previous research has been concerned with short-term (e.g., Kraft and Brainard²⁹) changes in the illuminant. There is some evidence that the visual system may require a number of days to recover from medium-term adaptation.^{30,31} For example, the recent work by Neitz et al.³¹ reports that unique yellow settings can shift by about +/- 4 nm after subjects adapt to 'red' or 'green' light for a number of hours per day over several days, and that the visual system can take about 10 days to return to the pre-adaptive state.

We have tested the locus of the achromatic point in observers before cataract surgery and for up to one year after cataract surgery to determine the time course of renormalization following the removal of a cataractous lens to which the person has presumably adapted over a number of years. Stimuli were presented on a calibrated CRT and chromaticity was adjusted in CIE $u'v'$ color space with luminance fixed at 30 $\text{cd}\cdot\text{m}^{-2}$. The 9.5° test stimulus flashed on and off at 3 s intervals to reduce adaptation to the stimulus. The starting chromaticity of the stimulus was selected randomly. Settings were made before surgery and at various intervals after surgery up to one year. The stimuli were viewed monocularly.

The settings for one observer (age 71) are shown in Figure 5. After surgery, there is a large shift in the achromatic point in the yellow direction, from a to b in the figure. Much of this effect is expected from removal of the cataractous lens and the change in the retinal stimulus. However, the achromatic point slowly drifts back in the direction of the achromatic point before surgery, reaching a fairly stable value at about three months after surgery. Figure 5 shows the locus of the achromatic point after one year. Tests on other subjects show a similar pattern of results.

Neitz et al.³¹ found inter-ocular transfer of color appearance shifts and suggested that the changes they recorded were due to cortical processes. We did not find this to be the case in our study. For example, the subject presented in Figure 5 was tested in her fellow eye which had a cataractous lens removed 8 months prior to the 'test' eye. There was little change in the settings over the same period as the 'test' eye. This suggests most of the long-term adaptation effects studied here, and by inference associated with normal aging, occur at a site prior to binocular combination.

The post-surgery settings for the subject presented in Figure 5 were converted to cone responses using Smith-Pokorny fundamentals.³² Most of the differences in achromatic settings can be accounted for by changes in S-cone response which might be expected in view of normal lens aging having its greatest effect on S-cone stimulation and also for various phases of daylight.²

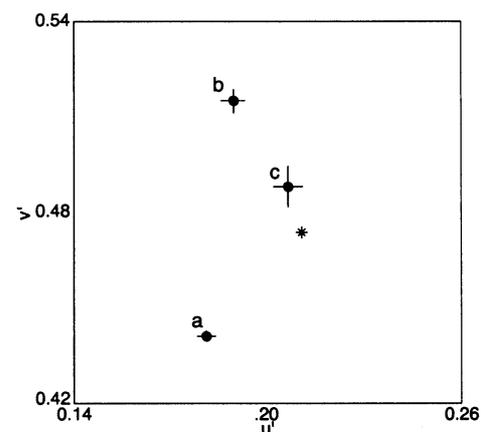


Fig. 5. Locus of average achromatic setting in CIE $u'v'$ chromatic coordinates for one observer (a) before cataract removal, (b) 1 day post-surgery and [c] 12 months post-surgery. Asterisk is equal-energy white.

6. CONCLUSIONS

Color appearance was probed in different regions of color space and using several different methods, but in all cases the stability of perception across the life span is remarkable. Because the retinal stimulus is continually changing with age and there are losses in sensitivity of the receptors with age, stability across the life span would only seem possible if the visual system compensated for the changed inputs by renormalizing itself. This occurs over a much more protracted time scale than classical color constancy. Renormalizing the achromatic point, or the balance of chromatic mechanisms, seems to require as long as three months following removal of a cataractous lens.

The ability of the visual system to maintain stable color perception despite the large physiological variations with aging has a number of important implications. First, measures of visual sensitivity may be poor predictors of perceptual experience, and thus direct measures of appearance are important for characterizing the consequences of visual aging. Second, the compensations considered here are not restricted to color vision or aging, but probably reflect a general design principle in visual coding. For example, sensitivity varies dramatically with retinal eccentricity, yet the world does not appear to depend on where we fixate, and analogous processes of normalization may compensate for sensitivity differences between the fovea and periphery (e.g. owing to differences in macular pigment). Similarly, aging and eccentricity alter most aspects of vision, and these may be normalized in similar ways. For example, visual acuity declines with both senescence and peripheral viewing, yet threshold contrast sensitivity fails to predict the contrast constancy observed in suprathreshold patterns,³³ or the stable perception of image focus across eccentricity.³⁴ Finally, the fact that these adjustments are calibrating the visual system for properties of the physical world implies that they not only maintain perceptual constancy within observers, but also across observers. That is, if a young and old individual agree on the stimulus they call white, then this is because they both are normalized for a common “ageless” stimulus in their environment.

Supported by the National Institutes of Health (EY10834 and AG04058) and a Jules and Doris Stein Research to Prevent Blindness Professorship.

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