

The Role of Lenticular Senescence in Age-Related Color Vision Changes

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PURPOSE. It has been reported that greater age-related losses in sensitivity occur for short-wavelength visual stimuli than for medium- and long-wavelength visual stimuli. The purpose of the current experiment was to determine to what extent optical, receptor, and postreceptor factors contribute to these age-related changes in color vision.

METHODS. One hundred two observers (ages 18–87) completed a minimum motion task to determine isoluminance between red and green and between red and blue. A motion-nulling task was also performed to assess the L-M postreceptor chromatic mechanism.

RESULTS. No significant age-related changes occurred in red-green isoluminance values. Red-blue isoluminance values showed a significant and systematic decrease with age in observers with phakic eyes. Pseudophakic eyes in older subjects performed this task as well as phakic eyes in young subjects. The motion-nulling results demonstrated small age-related losses in the postreceptor color mechanisms.

CONCLUSIONS. The findings of this experiment, particularly those of the red-blue isoluminance task, indicate that the optical factor of lenticular senescence is the main contributor to the age-related changes observed in color vision. A model based on age-related changes in lenticular absorbance shows good fit with the experimental data of observers with phakic eyes, suggesting that optical factors are the main cause of the age-related changes in these color vision tasks. (*Invest Ophthalmol Vis Sci.* 2003;44:3698–3704) DOI:10.1167/iov.02-1191

There are many reports of losses in visual function associated with nonpathologic aging. For example, there is a reported loss in sensitivity to second-order motion stimuli.¹ Numerous studies report age-related changes in color vision (see, for example Refs. 2–4). Age-related losses in the sensitivity of the long (L), medium (M), and short (S) cone mechanisms have also been reported.⁵ Among age-related changes in color vision, heterochromatic flicker photometry and brightness-matching experiments have demonstrated that infants have a greater relative sensitivity to short-wavelength light than do

adults⁶ and that a systematic decrease in relative sensitivity to short-wavelength light occurs after 10 to 20 years of age.^{7–9} Similar conclusions have been reached with different methods of investigation.¹⁰ The purpose of this research was to evaluate the contribution of various factors to these age-related losses in relative sensitivity to short-wavelength stimuli.

Optical factors such as changes in the ocular media have been suggested to contribute to this age-related change in color vision. It is generally agreed that the optical density of the intraocular lens increases in a linear fashion throughout the life span.^{11–14} This increase in optical density results in greater decreases in retinal illuminance at short wavelengths, and in more modest decreases at longer wavelengths. Because of this, light reaching the S-cones will be attenuated more with increasing age than light reaching the M- and L-cones, thus selectively decreasing sensitivity to short-wavelength stimuli.

Receptor factors could also explain age-related changes in color vision. Greater age-related declines in the sensitivity of the S-cone mechanism in comparison with those of the other cone mechanisms have been reported.^{15–17} It may be that S-cones show a greater decrease in sensitivity with age because they are more easily damaged by actinic insults and a variety of diseases than M- and L-cones. Another receptor factor that could account for age-related changes in color vision is the observed age-related decrease in photopigment density.¹⁵

Age-related changes in postreceptor color mechanisms could also contribute to the greater loss in sensitivity to short wavelength stimuli than to longer wavelength visual stimuli. Anatomic evidence demonstrates that there is a decrease in the number of retinal ganglion cells with age.^{17–20} Other postreceptor factors, such as cortical cell loss or reduction in thickness of myelination could also affect processing of color stimuli. If the losses occur primarily within chromatic opponent color cells, the selectivity of these losses would result in a greater loss in sensitivity to chromatic stimuli than to luminance stimuli.

To assess the relative contribution of the optical and receptor factors to age-related changes in color vision, isoluminance was measured in observers of different ages. If lenticular senescence were the main cause of age-related changes in color vision, one would expect that age differences would largely disappear once this factor was controlled for. Finally, a motion-nulling method was used to determine whether selective age-related losses in sensitivity occur in the postreceptor chromatic mechanism in comparison with the luminance mechanism.

METHODS

Apparatus and Stimuli

Stimuli were generated with a computer (Macintosh PowerMac 7300/200; Apple Computer, Cupertino, CA) equipped with a monitor (PT 813 CRT; ViewSonic, Walnut, CA). The CIE x, y coordinates of the monitor were 0.61, 0.34 for the red phosphor, 0.29, 0.58 for the green phosphor, and 0.14, 0.06 for the blue phosphor. A minimum motion technique^{21,22} was used to determine isoluminance between the components of a chromatic grating.

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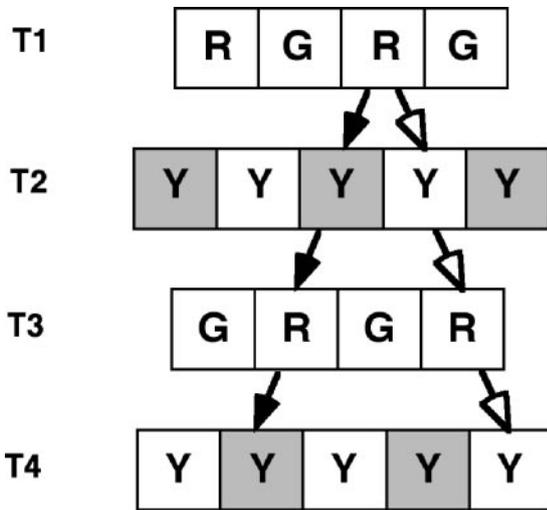


FIGURE 1. Representation of a minimum motion stimulus at four temporal intervals. Two gratings are presented 90° spatially and temporally out of phase: a red-green chromatic grating and a bright yellow-dark yellow achromatic grating. The gratings on the even intervals were 180° temporally and spatially out of phase, as were those on odd intervals. Depending on the relative luminance of the red and green component of the chromatic grating, the observer saw motion in a direction consistent with the relative luminance. For example, if red had a greater luminance than green, the observer saw movement from the red portion of the chromatic grating to the bright yellow portion of the achromatic grating (*open arrows*). If red was darker than green, the observer saw motion in the opposite direction (*filled arrows*). At isoluminance, only counterphase flicker is perceived.

A fixation point was presented at the center of the monitor at all times during testing. Vertical sinusoidal gratings were presented through a circular aperture with a diameter subtending 4° of visual angle. All stimuli were presented centrally. Gratings had a spatial frequency of 0.5 cyc/deg to minimize potential luminance artifacts from the transverse chromatic aberration that is most evident at higher spatial frequencies.²³ The temporal frequency of the gratings was 2 Hz. The mean luminance of one of the components of the chromatic grating remained constant, whereas the mean luminance of the other component of the grating was adjusted by the experimenter until isoluminance was found for an observer.

The luminance modulation of the red-green stimulus can thus be represented as

$$R(x,t) = 0.5 \cdot L_R \cdot \left\{ \begin{aligned} &[1 + m \cdot \sin(2\pi f_s x) \cdot \sin(2\pi f_T t)] \\ &+ [1 + \cos(2\pi f_s x) \cdot \cos(2\pi f_T t)] \end{aligned} \right\} \quad (1)$$

$$G(x,t) = 0.5 \cdot L_G \cdot \left\{ \begin{aligned} &[1 + m \cdot \sin(2\pi f_s x) \cdot \sin(2\pi f_T t)] \\ &+ [1 - \cos(2\pi f_s x) \cdot \cos(2\pi f_T t)] \end{aligned} \right\} \quad (2)$$

where $R(x,t)$ and $G(x,t)$ are the luminances of the monitor's red and green phosphors as a function of horizontal position (x) and time (t); L_R and L_G are the mean luminances of the red and green phosphor respectively; f_s and f_T are the spatial and the temporal frequencies of the gratings, respectively, and m is the Michelson contrast of an achromatic grating. The luminance contrast of the achromatic grating was 10% Michelson contrast. Depending on the relative mean luminances of the red and green phosphors, the observer perceives motion toward the left, the right, or, at isoluminance, counterphase flicker. An illustration of the minimum motion stimulus is shown in Figure 1, and more detailed explanation of the minimum motion stimulus can be found in Cavanagh et al.²² and Anstis and Cavanagh.²¹ In the red-green isoluminance task, the mean luminance of the green phosphor was

held at 18 cd/m² and the mean luminance of the red phosphor was varied. A similar stimulus was used to determine isoluminance between red and blue in which the red and blue phosphors were modulated. In the red-blue isoluminance task, the mean luminance of the blue phosphor was held constant at 7 cd/m².

Age-related changes in postreceptoral chromatic mechanisms were assessed with a motion-nulling method. An isoluminant red-green grating drifting toward the right was presented, superimposed on a bright yellow-dark yellow achromatic grating drifting in the opposite direction. Both gratings had a spatial frequency of 0.5 cyc/deg and drifted at a velocity of 4° per second (temporal frequency of 2 Hz). The contrast of the isoluminant red-green grating remained constant while the luminance contrast of the achromatic grating that drifted in the opposite direction was adjusted.

The luminance modulation of the red and green phosphors for this task can be represented as

$$R(x,t) = R_{\max} \cdot \left\{ 1 + \left[\frac{m \cdot \sin(2\pi f_s x - 2\pi f_T t) + \sin(2\pi f_s x - 2\pi f_T t)}{1 + m} \right] \right\} \quad (3)$$

$$G(x,t) = G_{\max} \cdot \left\{ 1 + \left[\frac{m \cdot \sin(2\pi f_s x - 2\pi f_T t) - \sin(2\pi f_s x + 2\pi f_T t)}{1 + m} \right] \right\} \quad (4)$$

where R_{\max} is the maximum luminance of the red phosphor and G_{\max} is the maximum luminance of the green phosphor. Similar to the minimum motion technique, depending on the contrast of the achromatic grating, observers perceive motion in the direction of the chromatic grating, the achromatic grating, or counterphase flicker. Cavanagh and Anstis²⁴ describe this motion-nulling stimulus in greater detail.

Observers

Observers were recruited among the patients and staff members of the Sir Mortimer B. Davis Montreal Jewish General Hospital Department of Ophthalmology. One hundred two observers between 18 and 87 years of age (mean age, 56.52 ± 19.01 years [SD]) were tested. Sixty-seven of these observers had phakic eyes and 35 pseudophakic (model LX10BD lens; Alcon, Fort Worth, TX) eyes. Observers were not experienced psychophysical observers and were naïve to the hypotheses of the experiment.

Observers were required to have best corrected visual acuity of 20/30 or better in the eye that was tested. This criterion was chosen to allow older observers to participate in the experiment. It may be noted that while a best corrected visual acuity of 20/30 may be normal for elderly observers, it is clearly too low for young observers (below 40 years of age). However, because all the young observers (age <40 years) who took part in the experiment had a best corrected visual acuity of 20/20, these concerns were put to rest. Normal visual fields and the absence of ocular disease at their most recent examination—refraction (best corrected visual acuity), ophthalmoscopy, biomicroscopy, tonometry, stereoscopy, central and peripheral field of vision—were also required of participants. Finally, normal color vision as assessed by H-R-R pseudoisochromatic plates and a D-15 color vision test was also a prerequisite for inclusion.

Procedure

Observers were tested in accordance with the Declaration of Helsinki for research involving human subjects. All testing was conducted monocularly in the observer's eye that had the best visual acuity. Stimuli were viewed through natural pupils. Observers viewed the display at a distance of 57 cm and were instructed to keep the gaze on the central fixation point. In each observer, isoluminance was measured between the red and green phosphors of the monitor to deter-

mine the effects of age on red-green isoluminance. Determining red-green isoluminance also allowed for the assessment of the L-M postreceptoral chromatic mechanism in a minimum motion task.

Isoluminance was also measured between the red and blue phosphors. The purpose for measuring isoluminance between the red and blue phosphors of the monitor was not to assess any type of postreceptoral mechanism. Rather, red-blue isoluminance was determined because work by Faubert²⁵ has demonstrated that, when comparing the spectral energy profile of the different phosphors, the red phosphor has the narrowest bandwidth. Of the three phosphors, the red phosphor is also the least absorbed by the aging lens.^{13,14,26} In contrast, the greatest age-related losses in sensitivity are reported for short wavelengths,⁷⁻¹⁰ and light coming from the blue phosphor is the most absorbed by the aging lens.^{13-14,26} Measuring isoluminance between red and blue thus provides a means of assessing the contribution of optical factors to changes in isoluminance values.

In the minimum motion task, observers were instructed to report the perceived direction of a grating's motion (left or right) and to report when they could not perceive any direction of motion. Depending on the observer's reported perceived direction of motion, the experimenter adjusted the mean luminance of one of the components of the chromatic grating with the mouse by either an increase or a decrease. This method of adjustment was chosen instead of staircase procedures or the method of constant stimuli because observers were tested in a clinical setting and were available for only a limited time. The usual method of adjustment in which the observers perform the adjustment themselves was modified because many older observers were unfamiliar with computers and the use of a mouse. Having the experimenter perform the adjustments instead of the observers has the added benefit of ensuring the validity of measurements from these inexperienced psychophysical observers, who could have been responding to perceived flicker resulting from stimuli that are not isoluminant (for an explanation, see Cavanagh et al.²²). To ensure that the experimenter used only the responses of the observers, the experimenter did not view the monitor that observers viewed during testing. Furthermore, the experimenter is a deuteranope, and thus had to rely on the responses of observers. The color luminance contrast of the chromatic grating (C) was recorded at the end of each trial, when observers indicated that they saw no net direction of motion. This value was obtained by

$$C = (R_{\text{MOD}} - G_{\text{MOD}})/(L_R + L_G) \quad (5)$$

where R_{MOD} is the amplitude of luminance modulation of the red phosphor and G_{MOD} of the green phosphor. Color luminance contrast for a red-blue isoluminance task was determined by using a similar function but with the red and blue phosphor luminance modulations and mean luminances instead of the red and green phosphors. Five measurements were taken for each testing condition.

After assessing red-green isoluminance, the L-M postreceptoral chromatic mechanism was assessed with a motion-nulling procedure. As in the procedure used to measure isoluminance, observers were instructed to report the perceived direction of motion and the point at which they could no longer see any direction of motion. In this experiment, the experimenter adjusted the luminance contrast of an achromatic grating depending on the observer's perceived direction of motion. The Michelson contrast of the achromatic grating was recorded at the end of each trial, when observers reported that they could not perceive any net direction of motion. The Michelson contrast of a luminance grating that nulls the motion of a chromatic grating is considered to be the chromatic grating's equivalent luminance contrast. As in the minimum motion procedure, five measurements were taken. If selective losses to postreceptoral chromatic mechanisms occur, then the luminance contrast necessary to null the motion of an isoluminant chromatic grating should decrease with increasing age. This would indicate a selective loss in contrast sensitivity to chromatic stimuli relative to achromatic stimuli.

RESULTS

Good within-subject reliability was found for both the minimum motion and the opponent motion tasks. For the red-green isoluminance task, a Cronbach α coefficient of 0.9869 was obtained. For the red-blue isoluminance task, the α coefficient was 0.9969. An α coefficient of 0.9693 was obtained for the motion-nulling task. Both young (less than 40 years of age) and old (older than 65 years) observers showed high within-subject variability. Young and old observers obtained α coefficient values of 0.9966 and 0.9969, in the red-blue isoluminance task, 0.9895 and 0.9825 for the red-green isoluminance task, and 0.9564 and 0.9678 in the motion-nulling task, respectively. Scatterplots of the isoluminance data for observers in condition red-green and for condition red-blue as a function of observer age are shown in Figures 2A and 2B, respectively. A Pearson correlation between age and isoluminance values was performed on the results. The values of a linear regression for the different experimental tasks are shown in Table 1. An ANOVA was performed on the correlation coefficients to determine whether they significantly differ from zero.

For observers with phakic eyes, in the red-green minimum motion task, the correlation coefficient ($r = -0.199$) was not significant ($F_{(1,65)} = 2.687, P > 0.05$). The correlation coefficient of phakic eyes on the red-blue isoluminance ($r = -0.777$) task was statistically different from zero ($F_{(1,65)} = 99.204, P < 0.001$). The correlation coefficient ($r = 0.264$) obtained by pseudophakic eyes on the red-green isoluminance task did not differ significantly from zero ($F_{(1,34)} = 2.542, P > 0.05$). Similarly, in the red-blue isoluminance task, the correlation coefficient of pseudophakic eyes ($r = -0.125$) did not differ significantly from zero ($F_{(1,34)} = 0.543, P > 0.05$). On the red-blue isoluminance task, pseudophakic eyes obtained results similar to those of the phakic eyes of young observers. An ANOVA found no statistically significant differences between the results in phakic eyes of observers less than 40 years of age and those of the older pseudophakic eyes ($F_{(1,57)} = 0.226, P > 0.05$).

The luminance contrast of an achromatic grating necessary to null the motion of a red-green chromatic grating as a function of age is shown in Figure 3. Pseudophakic and phakic eyes in observers of the same age obtained similar results in this test. Because of this, the data of pseudophakic eyes was added to that of phakic eyes for correlational analysis. The correlation coefficient ($r = -0.311$) between age and the contrast of an achromatic grating needed to null the motion of an isoluminant red-green grating was found to be statistically significant ($F_{(1,101)} = 10.795, P < 0.01$). It should be noted that although these correlation values are statistically significant, observer age accounts for only 14% of the variance observed in normal observers and approximately 10% of the variance for all observers in the motion-nulling task.

DISCUSSION

The absence of significant age-related changes in red-green isoluminance values indicates that optical and receptor factors do not significantly affect the relative sensitivity to one of these colors selectively. The significant correlation between age and red-blue isoluminance suggests that older observers with phakic eyes require a lower level of red luminance for red to be perceived as having the same luminance as blue. In contrast, observers with pseudophakic eyes obtained results similar to those of the youngest observers (observers younger than 30 years and in their 30s) in the red-blue isoluminance task. This indicates that the age-related decreases in relative sensitivity to short-wavelength light, as assessed by the minimum motion technique, can be accounted for by optical fac-

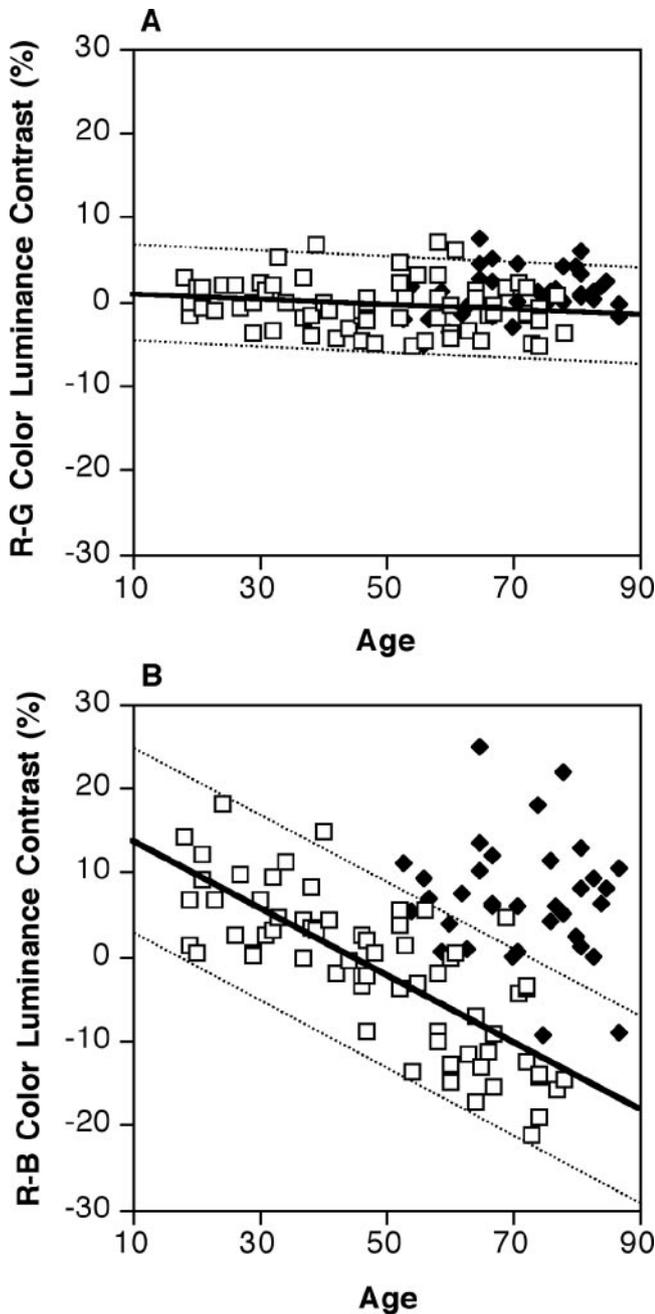


FIGURE 2. Isoluminance values for phakic and pseudophakic eyes as a function of observer age. (□) Results of observers with phakic eyes; (◆) results of observers with pseudophakic eyes. (A) Red-green color luminance contrast; (B) red-blue color luminance contrast. **Bold line:** best-fitting line for the results in phakic eyes. **Dotted lines:** 95% confidence bands of the linear regressions.

tors. Overall, these results are in agreement with earlier research suggesting that sensitivity to shorter wavelength stimuli is more affected than sensitivity to longer wavelength stimuli.⁷⁻⁹

If age-related changes at the level of the receptors preferentially affecting one type of receptor were the cause of the relative loss of sensitivity to short wavelength light, one would not expect those with pseudophakic eyes to obtain results similar to those of young observers in the red-blue isoluminance task. That no significant age-related changes were found in red-green and red-blue isoluminance values in pseudophakic

TABLE 1. Linear Regression Results for the Experimental Tasks

	Intercept	Slope	R ²
Phakic			
Red-green	1.176	-0.031	0.040
Red-blue	17.769	-0.400	0.604*
Motion-nulling	6.856	-0.028	0.140*
Pseudophakic			
Red-green	-4.396	0.074	0.070
Red-blue	13.081	-0.087	0.016
Combined			
Motion-nulling	6.731	-0.026	0.097*

* P < 0.05.

eyes suggests that there are no selective losses in the relative sensitivity of one cone mechanism. This is in agreement with earlier findings, which showed that all three types of cone lose overall sensitivity at a similar rate.¹⁷

The motion-nulling task found evidence of a small but significant age-related decrease in the sensitivity of the L-M postreceptoral chromatic mechanism in comparison with the luminance mechanism. However, one should be cautious when considering this result, because age accounts for only approximately 10% of the variance among all observers on this task. This age-related decrease in relative sensitivity to chromatic stimuli is not consistent with earlier literature suggesting that age-related losses in the luminance and chromatic pathways are nonselective,²⁷ although this discrepancy may occur because observer age accounts for only a small proportion of the variance. Because the postreceptoral losses in sensitivity to red-green chromatic motion were relatively small, it is unlikely that they account for much of the selective losses in sensitivity to short wavelength stimuli. Furthermore, it is unlikely that age-related losses in the sensitivity of the L-M postreceptoral system can account for the systematic age-related decrease in the results of our red-blue isoluminance task, because these losses were quite small.

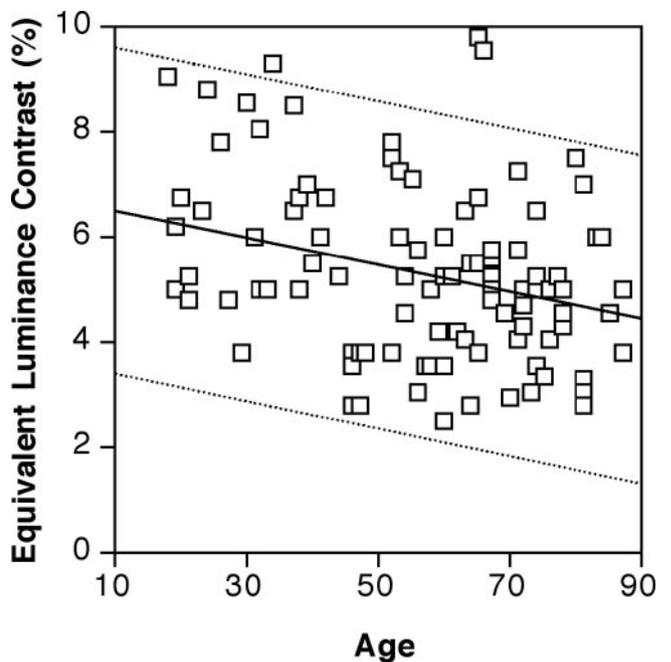


FIGURE 3. Equivalent luminance contrast results for all observers as a function of age. **Bold line:** best-fitting line for the results of phakic observers. **Dotted lines:** 95% confidence bands of the linear regressions.

It may be argued that, in the motion-nulling task, the drifting red-green grating did not isolate the L-M red-green postreceptoral mechanism and that there is a contribution of the S-(L+M) blue-yellow mechanism to the perception of chromatic motion.²⁸ Should this be so, it is also possible that the reported small age-related changes in the red-green motion-nulling task can reflect losses in the S-(L+M) postreceptoral mechanism. The isoluminant red-green grating used in these experiments stimulated both chromatic mechanisms, although it stimulated the L-M system preferentially. Research on chromatic motion studying the S-(L+M) system has found that chromatic gratings isolating this mechanism resulted in lower perceived speeds,^{29,30} even when matched for multiples of threshold.²⁹ In addition, when a chromatic grating stimulates both postreceptoral color mechanisms, perceived speed appears to be determined using a single mechanism.³⁰ Thus, because the chromatic grating stimulated the L-M mechanism preferentially, the L-M system is more sensitive to contrast, and the S-(L+M) appears to be less efficient at chromatic motion perception,^{24,29,30} it is probable that results reflect losses in the L-M chromatic system.

That older observers with pseudophakic eyes obtained results identical with those of the youngest observers on a red-blue isoluminance task suggests that lenticular senescence can account for most, if not all age-related changes found in phakic eyes on this task. To determine whether lenticular senescence alone could explain the age-related decrease in red-blue isoluminance, a model based on lens absorbance as a function of age and wavelength¹⁴ was created.

This model describes the mean luminance of the red and blue phosphors as vectors in a color space. A representation of such a space is described in Figure 3.

The length of the L_R and L_B vectors represents the mean luminance of the red and blue phosphors, respectively, on a red-blue isoluminance task. In such a space, it is assumed that isoluminance is achieved when a certain distance is reached between the two vectors (k). This k vector is perpendicular to the vector representing blue luminance. This color space is illustrated in Figure 4. The value of k can be determined with the function

$$k = \sqrt{L_R^2 - D_B^2} \tag{6}$$

If lenticular senescence can account for all the age-related changes on a red-blue isoluminance task for phakic observers, the value of k remains constant with age once this factor is taken into account.

To determine the value of k , it was necessary to determine the amount of light from the monitor's blue phosphor reaching the retina. To do this, the spectrum of the blue phosphor of the monitor was filtered using the lens absorbance values of Weale.¹⁴ Because the pupil size of observers was not measured during testing, it is assumed that all observers had a pupil diameter of 4 mm during this period. It should be noted that although pupil size may attenuate light reaching the retina, these effects are not wavelength selective. Therefore, senile miosis by itself should not cause a change in the relative luminances of the red and blue phosphors reaching the retina. Moreover, pupil size also diminishes for observers with pseudophakic eyes, and yet, they obtain results similar to those of the young with phakic eyes on the red-blue isoluminance task. In addition, if pupil size were an important factor on red-blue isoluminance, one would expect age-related changes in these values for observers with pseudophakic eyes. We observed no evidence of this. Because absorbances¹⁴ were available only at wavelengths of 380, 400, 420, 440, and 460 nm, the best-fitting exponential function was used to estimate lens absorbance at

intermediate wavelengths for each age. These values were used to determine the transmissivity (T) of the ocular lens as a function of wavelength and age (A) with the formula

$$T(\lambda, A) = 10^{-D(\lambda, A)} \tag{7}$$

where D is the absorbance of the ocular lens at a given wavelength and age. Weale's values of lenticular absorbance¹⁴ indicate that the amount of long-wavelength light absorbed by the crystalline lens at any age is not significant. Because of this, the red phosphor luminance values were not filtered. Reflectometry results show this clearly.²⁶

These values of lens transmissivity as a function of wavelength were used to estimate the proportion of light from the blue phosphor transmitted by the crystalline lens at different ages using the formula

$$T_B(A) = \sum T(\lambda, A) \cdot P(\lambda) \tag{8}$$

where $P(\lambda)$ is the proportion of the blue phosphor's output at a given wavelength over the total output of the phosphor. This allowed us to evaluate the transmittance of crystalline lens to the blue phosphor in observers aged 20, 40, 60, and 80 years. These values were then used to estimate the proportion of light from the blue phosphor transmitted by the lens in observers of ages of 30, 50, and 70 years.

The estimated transmissivity of the crystalline lens to the blue phosphor was used to determine the amount of light from the blue phosphor transmitted to the retina at a given age with the function

$$L'_B(A) = L_B \cdot T_B(A) \tag{9}$$

where $L'_B(A)$ is the filtered mean luminance of the blue phosphor at a given age, once lenticular senescence is taken into account. This filtered value of the blue phosphor's mean luminance was used to determine k at the age of 20 with the following equation

$$k = \sqrt{L_R^2(20) - L_B'^2(20)} \tag{10}$$

To estimate the mean luminance of the red phosphor, which appears isoluminant with the filtered values of blue luminance at this age, the color luminance contrast results on a red-blue isoluminance task was estimated by using the best-fitting regression line in Figure 2B.

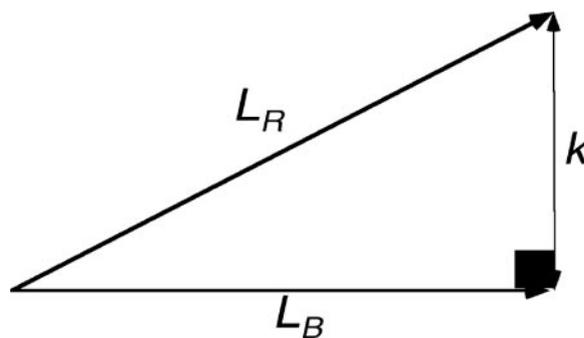


FIGURE 4. Representation of the mean red and blue luminances as vectors in a color space. The length of the vectors represents the mean luminance of the red and blue phosphors. Isoluminance is achieved when a psychological distance of k is reached between the two vectors. Once optical filtering is taken into account, it is assumed that this psychological distance remains constant with age.

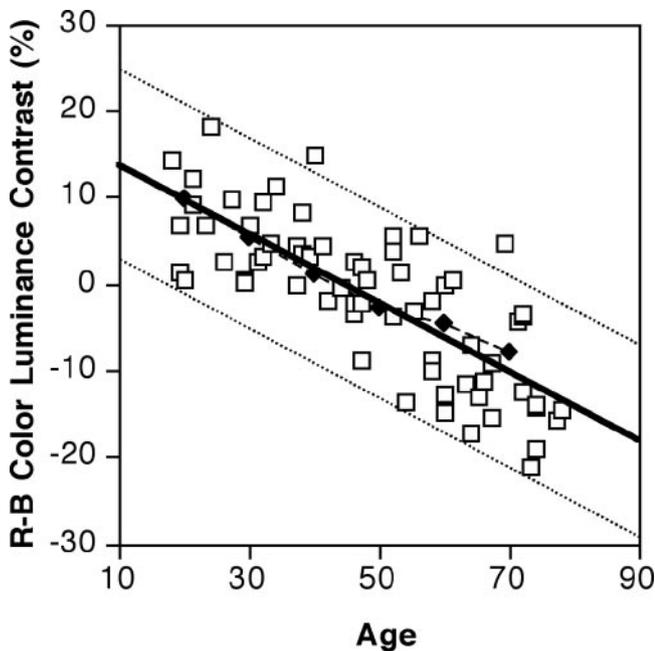


FIGURE 5. Model predictions versus experimental data of red-blue isoluminance values as a function of age. **Bold line:** best-fitting linear regression line of color luminance contrast as a function of age. **Open squares:** individual results of observers with phakic eyes on the red-blue isoluminance task. **Dotted lines:** 95% confidence bands of a linear regression. **Dashed line, filled diamonds:** predictions of a model based on age-related changes in lens absorbance.

The k value determined in equation 10 and the filtered mean luminance of the blue phosphor were used to estimate the predicted mean red luminance (L'_R) necessary to achieve isoluminance with blue at different ages. This was determined by

$$L'_R(A) = \sqrt{L_B'^2(A) + k^2}. \quad (11)$$

The predicted mean luminance of the red phosphor was used to determine the predicted color luminance contrasts as a function of age with equation 1. The predicted color luminance contrasts made by this model and the experimental results are shown in Figure 5. As can be seen, the model shows good fit with the best-fitting regression line for red-blue isoluminance results. This suggests that the optical factor of lenticular senescence can account for the age-related decrease in red-blue isoluminance values alone. This is concordant with the finding that observers with pseudophakia performed similarly with younger observers with phakic eyes on a red-blue isoluminance task (see Fig. 2B). This is also consistent with earlier suggestions that no selective losses occurred in the various cone mechanisms.¹⁷

That older observers with pseudophakic eyes performed as well as younger observers on the red-blue isoluminance task led us to conclude that lenticular senescence can account for the decrease in sensitivity to short-wavelength visual stimuli observed in the experiments discussed in this article. No evidence was found for a selective loss of one cone type in normal aging. This conclusion is also supported by the fact that a model based on lenticular senescence showed such good fit with the data in the red-blue isoluminance task. Furthermore, our data showed a small but significant decrease in the sensitivity of postreceptoral chromatic mechanism relative to luminance contrast sensitivity. It is not currently possible to determine whether there is a selective loss in one of the two

postreceptoral chromatic mechanisms. A motion-nulling task seems ill-suited as a method of comparing losses in these two systems, because the S-(L+M) mechanism does not seem to contribute as much to motion processing.^{22,24,25,29,30}

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