Technical Review

Senescent Changes in Color Discrimination and Color Appearance

Keizo SHINOMORI

Department of Information Systems Engineering,
Kochi University of Technology
185 Miyanokuchi, Tosayamada-cho, Kami-gun, Kochi 782-8502, Japan

Received July 27, 1999

ABSTRACT

Age-related anatomical and physiological changes in the human visual system have been reported such as an increase in the density of the lens, a reduction of pupil size and loss of retinal ganglion cells. Although the retinal stimulus and neural signals are strongly affected by such age-related changes, color appearance is stable throughout the life-span because of parallel losses of cone sensitivities and other compensation mechanisms related to color constancy. On the other hand, there is a loss of sensitivity in color discrimination due, in part, to the reduction of retinal illuminance. The results of recent experimental studies by the author and colleagues indicate that this loss in discrimination is not only caused by the reduction of retinal illuminance, but also by a decrease in the signal-to-noise (S/N) ratio in neural pathways processing signals from S-cones and antagonistic signals from L- and M-cones. This change can be considered as a sort of a trade-off between maintaining a constant signal level from the cones through the life-span and decreasing the signal-to-noise ratio in the human visual system. These results suggest some possible methods for making safer and more comfortable visual environments for the elderly.

1. Introduction

Age-related changes to the anatomy and physiology of the human visual system have been reported. In terms of pre-retinal changes, the ocular media density increases with age, primarily due to absorption changes in the lens. This causes not only a reduction in retinal illuminance, but also changes the spectral radiance of stimuli on the retina¹⁾. The reduction of pupil size with age, sometimes called "senile miosis," also decreases the retinal illuminance of stimuli²⁾. These changes dramatically affect the physical stimulation of the retina. The chromatic coordinates of Munsell color chips, for example, are shifted in a yellowish direction by the senescent increases of lens density³⁾. By these two factors, it is possible to explain accurately the data reported on age-related changes of the photopic luminous efficiency function measured by heterochromatic flicker photometry⁴⁾⁵⁾ and of the scotopic luminous efficiency function⁶⁾.

Several anatomical studies of the human retina indicate that there are no significant age-related losses in foveal cone density⁷⁾⁻⁹⁾. It has been reported, however, that the shape of the outer-segment of the cones changes with age¹⁰⁾. This shape change results in a change in the orientation and alignment of the "disk-like" membranes and may be expected to cause a reduction of cone sensitivities. The results of psychophysical tests with Stiles' two-color threshold method shows that cone sensitivities decrease with age by about 0.13 log unit per decade in all cone types¹¹⁾.

Regarding post-receptoral changes, anatomical investigations indicate that there is about a 25% loss of ganglion cells subserving the central area of the retina between about 30 and 70 years¹²⁾¹³⁾. This is expected to reduce

efficiency of signal transfer in neural pathways.

The main question of this paper is whether or not such senescent changes cause changes in color appearance and color discrimination. It is concluded that although color appearance changes little with age, the ability to discriminate color is reduced significantly with age under certain conditions.

A preliminary version of this paper has been presented in oral form¹⁴⁾.

2. Senescent changes in color appearance

2.1 Color appearance is stable across the life span.

Age-related changes in color appearance have been measured with several different methods and in different regions of color space. For example, the wavelengths of spectral unique hues were measured for 50 observers ranging from 13 to 74 years of age in natural (Newtonian) view¹⁵⁾. The results show that there is no senescent change in the wavelengths of unique blue and unique yellow. In contrast, the wavelength of unique green shifted slightly toward shorter wavelengths with increasing age. Nonlinearity in signal processing by the yellow-blue chromatic opponent channel might affect the age-related change of unique green. Overall, unique hues of monochromatic lights are relatively stable throughout the life-span. Neutral points (achromatic loci) were measured in terms of additive mixtures of two wavelengths corresponding to unique blue and unique yellow, and verified with mixtures of 600 nm monochromatic light and the complementary wavelength¹⁶⁾. There is no change with age in the chromaticity coordinates of these neutral points. Thus, the

white point is not affected by the age-related changes of spectral transmittance of lens.

Hue and saturation of OSA color chips were measured by a color-naming method with natural viewing conditions¹⁷⁾. This experiment investigated the change of color appearance of broadband surfaces. The color naming results showed that the red-green and yellow-blue proportions do not change with age. This implies that the appearance of (object) color is stable with age. However, the proportion of the chromatic component relative to the achromatic component was slightly reduced with age on the color chips of lower values. These results mean that there is no hue shift with age, but saturation is reduced if it is measured with some color chips in natural view. For further investigation, the saturation function was precisely measured with monochromatic lights in the Maxwellian view with equal (corneal) illuminance and with equal retinal illuminance¹⁸⁾. These results indicate that there is no statistically-significant difference in the saturation function between young and old age groups in both conditions. Because there is no change with age in the estimated saturation measured with monochromatic lights, it is expected that small age-related reductions of the chromatic component in the color-naming method are caused by a change in the spectral distribution of color chips on the retina or possible influences of stray light which increases with age¹⁹⁾.

2.2 Why color appearance is so stable across the life-span?

As indicated by the experimental data described above, even though the physical change in stimulation on the retina is relatively large with increasing age, there is little age-related change in color appearance. There are two possible hypotheses that may explain this stability of color appearance.

(1) Parallel loss of cone sensitivities

There are significant losses of cone sensitivities with age but the decline of sensitivities in each cone type is nearly the same¹¹⁾. This parallel loss of cone sensitivities helps to balance relative responses of cones as long as responses of chromatic-opponent channels are linearly related to the signals from cones, because color appearance is basically determined by the relative intensity of signals from the three types of cone.

It should be noted that the magnitude of the losses in cone sensitivity with age depend on the level of adaptation. This was demonstrated in a study of detection mediated by an S-cone mechanism²⁰⁾. Increment thresholds of Stiles' π_1 mechanism were higher in old observers than young observers at lower field intensities, but the thresholds were almost the same for old and young observers at high field intensities.

(2) Color constancy type of compensation

Age-related changes in the spectral radiance on the retina can be compensated theoretically by color constancy mechanism, such as a von Kries type of adaptation. In the von Kries type of adaptation, responses of cones to the stimulus (denoted by L'_c , M'_c and S'_c) are affected by adaptation to background illumination (denoted by L_{adapt} , M_{adapt} and S_{adapt}) as;

$$L'_c = k * L_c / L_{adapt}, M'_c = k * M_c / M_{adapt}, S'_c = k * S_c / S_{adapt} \quad (1)$$

Under this model, as well as the two-factor model of lens transmittance¹⁾, the appearance of Munsell color chips plotted on the cone response coordinates can be almost the same for different all age groups³⁾. Also, the appearance test on (only) a D₆₅ white stimulus was performed on young observers by changing the chromatic coordinates and luminance on a CRT to simulate age-related increases in light absorption by the lens from 50 to 80 year-old people³⁾. Such simulated D₆₅ white stimuli could still be perceived as unique white by young observers when the age in the simulation was under 66 years. The results of this experiment show that at least for the white stimulus, the short-term color constancy mechanism can explain the stability of color appearance for old observers under 66 years old but other compensation mechanism(s) must be expected for people over that age.

3. Senescent changes in color discrimination

It is well known that there are age-related losses in the ability to discriminate colors in many ordinary situations. This is supported by testing with the Fransworth-Munsell100-hue test which indicates tritan-like defects in older observers²¹⁾. This kind of defect is also found in younger observers when tested at lower illuminance levels. These results support the conclusion that age-related increases in error scores on the 100-hue test are mainly caused by the reduction of retinal illuminance because color discrimination becomes more difficult with the reduced light intensity. Thus, in natural viewing conditions, there is a loss of sensitivity in color discrimination. The next question is whether or not all age-related loss of color discrimination is caused only by the reduction of retinal illuminance or whether there are also losses resulting from neural changes.

3.1 Color discrimination by S-cone mechanism

My colleagues and I have recently measured age-related changes in color discrimination mediated by an S-cone mechanism²²⁾²³⁾. Stimuli were presented in Maxwellian view and equated in retinal illuminance by individual Heterochromatic Flicker Photometry (HFP) functions to control for age-related variations in pupil size and to compensate for the change of spectral transmittance of lens between observers, respectively. We also used a temporal two-alternative forced-choice (2AFC) method to measure thresholds in order to avoid possible criterion shifts associated with age.

Figure 1 shows the results plotted in terms of $\log \Delta S$ vs. $\log S$ coordinates. The abscissa, $\log S$, refers to the amount of excitation of S-cones by a standard field, in S-cone trolands. The ordinate, $\log \Delta S$, is the threshold for discriminating between the standard field and a test field, described in terms of the difference in the amount of S-cone excitation. As shown in the figure, the threshold increased with age at low S-cone excitation levels even though retinal illuminance was equated for each individual observer. However, there is no difference in threshold between age groups at higher S-cone excitation

levels. Because we used a constant retinal illuminance for each condition of S-cone excitation level, the age-related change in color discrimination by S-cone appears only on yellowish colors but not on whitish-blue colors.

Fig. 1 Geometric means of thresholds in chromatic discrimination mediated by S-cone for young (triangles), middle (squares) and old age-groups (circles) as a function of S-cone stimulation. Mean ages of each group are 25.8 (Young), 45.0 (Middle) and 69.5 (Old) years old. Error bars represent ± 1 SD. Curves show the best fitting functions for each data set calculated from equation (2). [Replotted from the original data in ref. 22.]

Equation 2 describes a model under the Weber-Fechner law that we used to analyze the data. In this equation, N denotes the Noise and W denotes the Weber fraction.

$$\text{S-cone mechanism: } \Delta S / (S+N) = W \quad (2)$$

Fits to the data using this model reveal that there is an age-related increase of noise and/or a loss of cone quantal efficiency (in this case, S-cone), but no change in Weber fraction. The sensitivity defined as the Weber fraction, itself is stable with age.

3.2 Wavelength discrimination

We have also measured age-related changes in wavelength discrimination using a Maxwellian-view optical system, with retinal illuminance equated by individual HFP functions, and use of a spatial 2AFC method²⁴⁾. Figure 2 shows mean wavelength discrimination thresholds for younger and older observers as a function of wavelength. The mean difference in thresholds at all wavelengths is about 3 nm between young and old observer groups. The amount of change in thresholds, however, is not systematically related to wavelength. The data were analyzed in terms of a modified version of the Boynton-Kambe color discrimination equations²⁵⁾²⁶⁾. In this model, discrimination thresholds are determined by signals

from S-cones and a second mechanism that combines responses from chromatically-opponent channels receiving signals from all three cone types (Equations 2, 3 and 4). N denotes the Noise and W denotes the Weber fraction. F is the output response of L- M- and S-cones mechanism as chromatically-opponent channels ($2M-L+S$ and $L-2M+S$).

$$\text{L-, M- and S-cones mechanism: } F = |2M-L| + k * S \quad (3)$$

$$\Delta F / (F+N) = W \quad (4)$$

Analyses of the wavelength discrimination functions using this model indicate that for discriminations mediated by signals from S-cones, there is an age-related increase in neural noise and/or a loss of cone response. This kind of age-related change is consistent with our findings described in the previous section²²⁾²³⁾. On the other hand, for wavelength discrimination determined by signals from L- and M-cones processed in chromatically-opponent channels, the increase in threshold with age is mainly caused by an increase in the Weber fraction. This means that the sensitivity of the L-M mechanism itself declines with age.

Fig. 2 Mean wavelength discrimination thresholds are shown for 4 younger (30.9 years) and 4 older (72.5 years) individuals measured with a spatial, 2-alternative, forced-choice method. Smooth curves are derived from the model (Equations 2, 3 and 4). [Replotted from original data in ref. 24]

4. Discussion

4.1 Senescent changes in color appearance and discrimination

In many cases, color appearance is stable through the life-span even while there is a loss in the ability to discriminate color differences. These effects are observed even with compensation for retinal illuminance. Because of senescent anatomical and physiological changes, signals from cones and responses from channels processing antagonistic cone signals have to be amplified more with increasing age to maintain color appearance. However, this appears to have the consequence of making the signal-to-noise (S/N) ratio worse with age and causes the loss in color discrimination in certain conditions, when signals are relatively weak, but not for all conditions. This can be considered as a sort of a trade-off between maintaining color appearance and losing the accuracy of color discrimination with aging of the human visual system²⁷⁾.

4.2 Suggestions for making a safer visual environment, for elderly people

As described above, senescent changes in the eye and visual pathways lead to a loss of retinal illuminance and reductions in cone sensitivities in the elderly. These age-related changes cause a loss of color discrimination at the lower cone excitation and/or signal response levels. Several strategies can be used to create better and safer visual environments for the increasing proportion of the population that is elderly. Unfortunately, current research does not permit precise values to implement these suggestions. In addition, more research is needed to understand the consequences for younger observers as it is not possible to quantify how improvements for the elderly will influence vision for younger individuals.

(1) Illuminance (luminance) control

Higher light levels can be used to compensate for the reduction of retinal illuminance in the elderly. However, we have to be careful with higher illuminance levels because discomfort glare may appear and the minimum illuminance at which this type of glare appears declines with age. Also, we have to think that the suitable intensity of illumination for the elderly should depend on the specific purpose of the illumination. In general, this illuminance control might also be better for younger people because acuity and color discrimination will be better under reasonably high illuminance conditions.

(2) Use color differences having higher S-cone excitation levels and/or higher L-M(M-L) signal response levels

Certain chromatic stimuli, such as sodium lights close to 570 nm monochromatic light, should be avoided because in this color, both S-cone excitation level and M-L (L-M) signal responses are near their minima and age-related losses in discrimination are near their maximum. In other words, the color difference most easily discriminated by the young is not necessarily the same for the elderly. We have to be careful to use this kind of color difference for signs and signals. It is expected that stronger responses make the color discrimination

easier for everyone.

(3) Use illuminants with high color rendering properties.

As explained above, it is important for the elderly to maintain high excitation and/or response levels by chromatic stimuli for effective color discrimination. Illuminants with lower color rendering properties, may result in signals from stimuli under such illumination that is not necessarily effective enough for the discrimination by the elderly compared to signals elicited by lights of a high color rendering property. The illumination of the high color rendering property is more comfortable for everybody although the energy cost will increase.

(4) Can we use illumination in which the spectral radiance in the short wavelength region is enhanced?

It is worth considering whether or not we should use illumination in which the spectral radiance in the short wavelength region is enhanced. At first glance, this strategy is attractive in view of age-related losses in chromatic discriminations mediated by S-cones, however, it is difficult suggestion to implement and may have unwanted side effects for both young and old. The advantage is that color discrimination is likely to improve with increases in short-wave light. With respect to color appearance, little additional short-wave light is needed to compensate for changes in lens absorption because of compensation mechanisms that are already effective. Thus, for young and old alike, color appearance may be altered somewhat in undesirable ways. Thus, the amount of add-back must be less than 100% of the short-wave light lost to the senescent lens. Not only might this result in unusual color appearance for young and old, but there are two additional complications. There may be more lens fluorescence from short wave light in older observers and this might lead to more glare in the elderly²⁸⁾. Also, there is an additional concern about the possible damaging effects of light which are thought to be greater for short wavelengths²⁹⁾³⁰⁾. So this recommendation is controversial. Further investigation and discussion should be required before implementing this strategy, and it is not advisable at present.

It should be emphasized that for the first three recommendations, the improvements in illuminations suggested here may also provide a better lighting environment for younger people. This fact will certainly help to draw attention to these improvements in illumination planning. More intensive investigations are required to find the practical methods and precise values as soon as possible to improve the quality of life for the elderly.

Acknowledgment

This research is supported by a Grant-in-Aid for Scientific Research (C) from the Ministry of Education, Science, Sports and Culture, and from the Japan Society for the Promotion of Science (C-2 10835026).

References

- (1) Xu, J., Pokorny, J. and Smith, V.: "Optical density of the human lens", J. Opt. Soc. Am. A, Vol. 14, pp.953-960 (1997).
- (2) Winn, B., Whitaker, D., Elliott, D. B. and Phillips, N. J.: "Factors affecting light-adapted pupil size in normal human subjects", Invest. Ophthalmol. Vis. Sci., Vol. 35, pp.1132-1137 (1994).
- (3) Okajima, K.: "Color Appearance and light efficiency of aged people. -Color adaptation experiment and lighting design using visual aging simulation-", (written in Japanese), In *Color Forum Japan '98* (pp. 37-44), Tokyo: Ren Associates (1998).
- (4) Ruddock, K. H.: "The effect of age upon colour vision-II. Changes with age in light transmission of the ocular media", Vision Res., Vol. 5, pp.47-58 (1965).
- (5) Kraft, J. M. and Werner, J. S.: "Spectral efficiency across the life span: flicker photometry and brightness matching", J. Opt. Soc. Am. A, Vol.11, pp.1213-1221 (1994).
- (6) Weale, R. A.: "Notes on the photometric significance of the human crystalline lens", Vision Res., Vol.1, pp.183-191 (1961).
- (7) Dorey, C. K., Wu, G., Ebenstein, D., Garsd, A. and Weiter, J. J.: "Cell loss in the aging retina", Invest. Ophthalmol. Vis. Sci., Vol. 30, pp.1691-1699 (1989).
- (8) Gao, H. and Hollyfield, J. G.: "Aging of the human retina", Invest. Ophthalmol. Vis. Sci., Vol. 33, pp.1-17 (1992).
- (9) Curcio, C. A., Millican, C. L., Allen, K. A. and Kalina, R. E.: "Aging of the human photoreceptor mosaic: evidence for selective vulnerability of rods in central retina", Invest. Ophthalmol. Vis. Sci., Vol. 34, pp.3278-3296 (1993).
- (10) Marshall, J.: "Ageing changes in human cones", In Shimizu, K. & Oosterhuis, J. A. (Eds.), *XXIII Concilium Ophthalmologicum, Kyoto, 1978* (pp.375-378), Amsterdam-Oxford:Elsevier North-Holland (1978).
- (11) Werner, J. S. and Steele, V. G.: "Sensitivity of human foveal color mechanisms throughout the life span", J. Opt. Soc. Am. A, Vol. 5, pp.2122-2130 (1988).
- (12) Curcio, C. A. and Drucker, D. N.: "Retinal ganglion cells in Alzheimer's disease and aging", Ann. Neurol., Vol. 33, pp.248-257 (1993).
- (13) Gao, H. and Hollyfield, J. G.: "Aging of the human retina", Invest. Ophthalmol. Vis. Sci., Vol. 33, pp.1-17 (1992).
- (14) Shinomori, K.: "Color discrimination and appearance of the elderly", In *24th Session of the CIE, WORKSHOP of Division 1, "AGING EFFECTS ON VISION"*, Warsaw: CIE, (1999).
- (15) Scheffrin, B. E. and Werner, J. S.: "Loci of spectral unique hues throughout the life span", J. Opt. Soc. Am. A, Vol. 7, pp.305-311 (1990).
- (16) Werner, J. S. and Scheffrin, B. E.: "Loci of achromatic points throughout the life span", J. Opt. Soc. Am. A, Vol. 10, pp.1509-1516 (1993).
- (17) Scheffrin, B. E. and Werner, J. S.: "Age-related changes in the color appearance of broadband surfaces", Color Res. and Appl., Vol. 18, pp.380-389 (1993).
- (18) Kraft, J. M. and Werner, J. S.: "Aging and the saturation of colors. 2. Scaling of color appearance", J. Opt. Soc. Am. A, Vol. 16, pp.231-235 (1999).
- (19) IJspeert, J.K., de Waard, P.W.T., van den Berg, T.J.T.P. and de Jong, P.T.V.M.: "The intraocular straylight function in 129 healthy volunteers; dependence on angle, age and pigmentation", Vision Res., Vol. 36, pp.699-707 (1990).
- (20) Scheffrin, B. E., Werner, J. S., Plach, M., Utlaut, N. and Switkes, E.: "Sites of age-related sensitivity loss in a short-wave cone pathway", J. Opt. Soc. Am. A, Vol. 9, pp.355-363 (1992).
- (21) Knoblauch, K., Saunders, F., Kusuda, M., Hynes, R., Podgor, M., Higgins, K. E. and de Monasterio, F. M.: "Age and illuminance effects in the Farnsworth-Munsell 100-hue test", Appl. Opt., Vol. 26, pp.1441-1448 (1987).
- (22) Scheffrin, B. E., Shinomori, K. and Werner, J. S.: "Contributions of neural pathways to age-related losses in chromatic discrimination", J. Opt. Soc. Am. A, Vol. 12, pp.1233-1241 (1995).
- (23) Shinomori, K., Scheffrin, B. E. and Werner, J. S.: "Rates of age-related declines of chromatic discriminations are the same for equiluminant stimuli lying on tritan and constant S-cone axes", In Dickinson, C. M., Murray, I. J., & Carden, D. (Eds.), *John Dalton's Color Vision Legacy* (pp. 287-297), London:Taylor & Francis, (1997).
- (24) Shinomori, K. and Werner, J. S.: "Individual variation in wavelength discrimination: task and model analysis", In *Proceedings of The 8th Congress of the International Colour Association, I* (pp. 195-198). Kyoto: The Color Science Association of Japan (1997).
- (25) Boynton, R. M. and Kambe, N.: "Chromatic difference steps of moderate size measured along theoretically critical axes", Color Res. and Appl., Vol. 5, pp.13-23 (1980).
- (26) Shinomori, K., Scheffrin, B. E. and Werner, J. S.: "Spectral mechanisms of spatially induced blackness: data and quantitative model", J. Opt. Soc. Am. A, Vol. 14, pp.372-387 (1997).
- (27) Shinomori, K.: "Age-related changes in color vision", (written in Japanese), In *Color Forum Japan '97* (pp. 89-96). Shinjuku, Tokyo: Ren Associates, (1997).
- (28) Elliott, D.B., Yang, K.C.H., Dumbleton, K. and Cullen, A.P.: "Ultraviolet-induced lenticular fluorescence: Intraocular straylight affecting visual function", Vision Res., Vol. 33, pp.1827-1833 (1993).
- (29) Harwerth, R. S. and Spering, H. G.: "Effects of intense visible radiation on the increment-threshold spectral sensitivity of the rhesus monkey eye", Vision Res., Vol. 15, pp.1193-1204 (1975).
- (30) Ham, W.T., Allen, R.G., Feeney-Burns, L., Marmor, M.F., Parver, L.M., Proctor, P.H., Sliney, D.H. and Wolbarsht, M.L.: "The involvement of the retinal pigment epithelium", In Waxler, M. & Hitchins, V. M. (Eds.), *Optical radiation and visual health* (pp. 43-67), Boca Raton, FL: CRC Press (1986).