Journal of the Optical Society of Korea
Vol. 17, No. 4, August 2013, pp. 344-349
DOI: http://dx.doi.org/10.3807/JOSK.2013.17.4.344

Computer Simulation for Gradual Yellowing of Aged Lens and Its Application for Test Devices

Bog G. Kim[1], Jeong-won Han[2], and Soo-been Park[2]*

[1]*Department of Physics, Pusan National University, Busan 609-735, Korea*
[2]*Department of Housing and Interior Design, Pusan National University, Busan 609-735, Korea*

(Received April 24, 2013 : revised July 1, 2013 : accepted July 1, 2013)

This paper proposes a simulation algorithm to assess the gradual yellowing vision of the elderly, which refers to the predominance of yellowness in their vision due to aging of the ocular optic media. This algorithm employed the spectral transmittance property of a yellow filter to represent the color appearance perceived by elderly people with yellow vision, and modeled the changes in the color space through a spectrum change in light using the yellow filter effect. The spectral reflectivity data of 1269 Munsell matte color chips were used as reference data. Under the standard conditions of a D65 illuminant and a 10° observer of 1964 CIE, the spectrum of the 1269 Munsell colors were processed through the yellow filter effect to simulate yellow vision. Various degrees of yellow vision were modeled according to the transmittance percentage of the yellow filter. The color differences before and after the yellow filter effect were calculated using the DE2000 formula, and the color pairs were selected based on the color difference function. These color pairs are distinguishable through normal vision, but the color difference diminishes as the degree of yellow vision increases. Assuming 80% of yellow vision effect, 17 color pairs out of (1269x1268)/2 pairs were selected, and for the 90% of yellow vision effect, only 3 color pairs were selected. The result of this study can be utilized for the diagnosis system of gradual yellow vision, making various types of test charts with selected color pairs.

Keywords : Simulation algorithm, Gradual yellowing, The elderly, CIE xyY, DE2000
OCIS codes : (330.1690) Color; (330.1730) Colorimetry; (330.4595) Optical effects on vision

I. INTRODUCTION

Human visual performance deteriorates with age due to the senile ocular system and other complex causes. Among the many characteristics of an aging eye, one of the most significant changes is the distorted color appearance in the range of blue and purple [1-6]. Although the ocular system, retina, optic nerve, and brain stage also affect the aging of the eyes to some degree [7-11], many studies that have examined the relationship between aging and color vision reported that the lens is the major element known to affect aging [2, 4]. Increasing the optical density of a crystalline lens causes changes in light transmittance through the eyes, and as the lens yellows with age, it absorbs a larger amount of short wavelength light in the visible spectrum between 450-470 nm [2-14].

Researchers have examined the effects of the aging of a human lens [2], and actual experiments on young and elderly subjects were performed to determine the effects of an aging human lens using a yellow filter to simulate the vision of the elderly. The results suggested that the yellowing of a human lens affects the color vision of the elderly, and a yellow filter worn by young subjects could simulate the visibility of the elderly [10]. Aging decreases the visibility of color targets [10] as well as the ability of chromatic discrimination compared to young subjects [15]. Despite the extensive research on the relationship between aging and the changes in the lens, most studies focused on the changes themselves, not on the influence of that change to the elderly. Color is one of the critical factors in the human living environment, and it influences the human perception and satisfaction in the environment. Therefore, changes in the perception and satisfaction of the elderly with their

*Corresponding author: sobpark@pusan.ac.kr
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environment and quality of life are defined operationally by their color discrimination ability [16-19].

In addition to a detailed investigation of the changes in the human lens, this study performed a computer simulation of the gradual yellowing of the human lens as well as its effects on color perception. Transmission characters of a Y2 filter were used to simulate the yellowing of an aged human lens, and its spectral function was calculated to develop an algorithm. The proposed simulation algorithm was used to develop a device to measure the gradual yellowing of elderly vision, which could be used to detect and cope with problems in color perception, and finally to improve the elderly environment.

II. METHODS AND ALGORITHMS

2.1. Method

An algorithm for simulating yellow vision was developed, which included the process of the color spectrum through a yellow filter and color difference calculation. In addition, a process of color selection based on the color differences was determined to identify the color pairs that were distinguishable in a normal vision state but indistinguishable with a yellow filter simulating yellow vision of the aged. All processes were carried out using Matlab 7.11 from Mathworks. The spectral reflectivity of the 1269 colors in the Munsell book with a matte color finish collection was used to evaluate the algorithm [20]. The original reflectivity was measured using a Perkin Elmer Lambda 18 spectrophotometer at wavelengths ranging from 380 nm to 800 nm at 1 nm intervals [20]. In this study, the reflectivity from 400 nm to 700 nm at 10 nm intervals was used. OPTPROP was used for the color space conversion and color difference calculation [21]. In the test algorithm, the yellow vision was simulated from the measured transmission spectrum of a commercial Y2 yellow filter for the cameras.

2.2. Modeling of Yellow Vision using Yellow Filter

The modeling of yellow vision was performed using the algorithm shown in Fig. 1. For a given reflectivity spectrum of the material (R(λ)) and illumination condition (I(λ)), the light spectrum (S(λ)) could be calculated using the following equation:

$$S(\lambda) = R(\lambda) \times I(\lambda). \tag{1}$$

From the light spectrum, which enters the lens of the eye, the CIE XYZ tristimulus values could be calculated using the following integral transformation:

$$X = \int S(\lambda) \times X(\lambda) d\lambda,\quad Y = \int S(\lambda) \times Y(\lambda) d\lambda,\quad Z = \int S(\lambda) \times Z(\lambda) d\lambda, \tag{2}$$

where X(λ), Y(λ) and Z(λ) are the tristimulus vectors defined in the CIE XYZ standard system, and X, Y and Z are the tristimulus values. Once the CIE XYZ values are calculated, the CIE LAB values, RGB values and CMYK values can be calculated using a matrix conversion formula. The chromaticity coordinates (xyz) were calculated from the CIE XYZ tristimulus values using following equations:

$$x = \frac{X}{X+Y+Z},\quad y = \frac{Y}{X+Y+Z},\quad z = \frac{Z}{X+Y+Z}. \tag{3}$$

$x+y+z=1$ and this transformation defines the CIE *xy*Y specification.

The yellow vision was next simulated using the yellow filter. If the transmission spectrum (F(λ)) of the given yellow filter is known, the light spectrum after the yellow filter (S'(λ)) can be modeled using the following equation:

$$S'(\lambda) = S(\lambda) \times F(\lambda). \tag{4}$$

In this calculation, the transmission spectrum of the yellow filter was modeled with a commercial Y2 filter from Kenko Co. which is normally used for the cameras. From this modified light spectrum, (S'(λ)), the CIE XYZ tristimulus values (X_y, Y_y, Z_y) of the yellow vision could be calculated using an integral transformation given using above equation. The other color coordinates can be transformed easily using the matrix conversion formula.

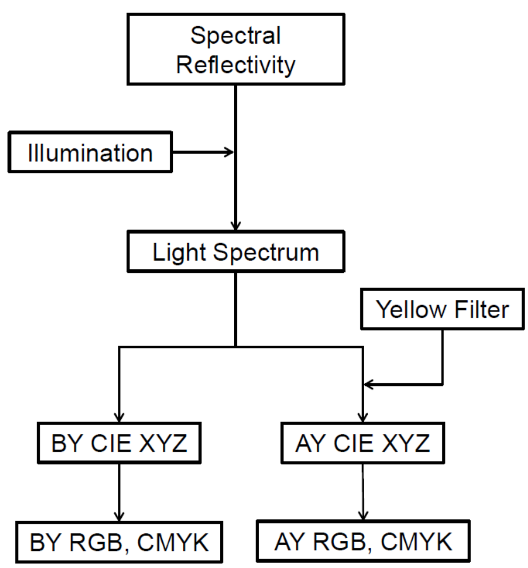


FIG. 1. Flowchart for the modeling of yellow vision using a yellow filter. BY is before the yellow filter and AY is after the yellow filter.

2.3. Color Difference

To calculate the color difference and selected sets of colors, the algorithm presented in Fig. 2 was developed using the CIE DE2000 Color difference formula [22, 23]. Traditionally, the CIE ΔE_{ab} derived from the CIE LAB values has been used to calculate large color differences. In the CIE xyY coordinates, equal changes in x, y or Y do not correspond to the perceived differences in the equal magnitudes. After a non-linear transformation from CIE xyY to CIE LAB coordinates, it is possible to calculate a color difference for two colors in CIE LAB space by calculating the Euclidean distance in the space. The perceptual color difference in CIE ΔE_{ab} is still non-uniform but forms an ellipsoidal shape. To correct this error, particularly with small color differences (< 5), the CIE recommends the CIE DE2000 color difference formula, which is basically an ellipsoidal shape correction to CIE ΔE_{ab}.

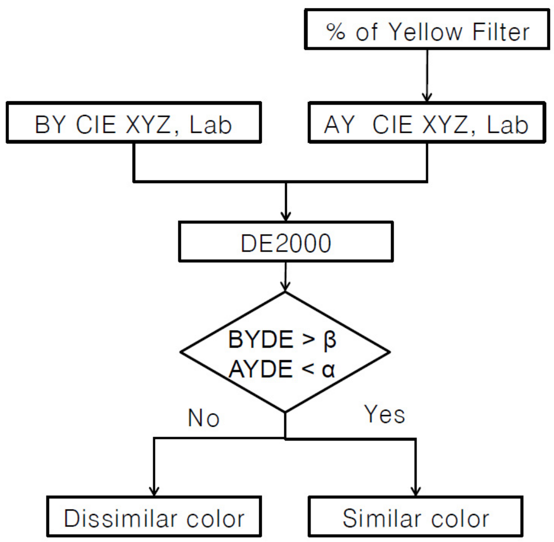


FIG. 2. Color difference calculation and color pair selection algorithm. BY is before the yellow filter and AY is after the yellow filter. BYDE and AYDE are N-by-N matrices of DE2000 color differences before the yellow filter and after the yellow filter, respectively.

Having the appropriate color difference formula of CIE DE2000, an algorithm for selecting the color sets can be developed. For a given N light spectrum (S(λ)), an N-by-N matrix of the color differences (BYDE) was calculated. Depending on the characteristics of the yellow filter and the degree of yellowing, the yellowed N light spectra (S'(λ)) were calculated, and an N-by-N matrix of the color differences after yellow filtering (AYDE) was also calculated. In the calculation, the two colors were treated as indistinguishable when the CIE DE2000 value was smaller than the lower boundary α, which is an arbitrary constant but can be adjusted later, and considered distinguishable when this value is larger than the upper limit β. Using this algorithm, the color sets for the yellow vision test were selected using the following criteria:

$$\begin{aligned} &BYDE2000 > \beta, \\ &AYDE2000 > \alpha. \end{aligned} \tag{5}$$

If the colors are selected by the above criteria, two colors are distinguishable before the yellow filter (normal vision) but are indistinguishable after the yellow filter (simulating the yellow vision).

III. RESULTS AND DISCUSSION

The simulation model for yellow vision is based on the spectral functions of the colors and filters [20, 22, 24]. Fig. 3(a) shows the spectral reflectivity of 120 colors selected from the 1269 Munsell color data. The spectral reflectivity values are defined from 0 to 100% and the wavelength range used for the calculation was 400 nm to 700 nm. Fig. 3(b) shows the transmission spectrum of the Y2 color filter from 400 nm to 700 nm. The spectrum was almost uniform over 90% between the wavelengths, 470 nm to 700 nm, and decreased sharply outside of these wavelengths, approaching zero, which is a characteristic of the yellow filter. This transmission character can be modeled as a

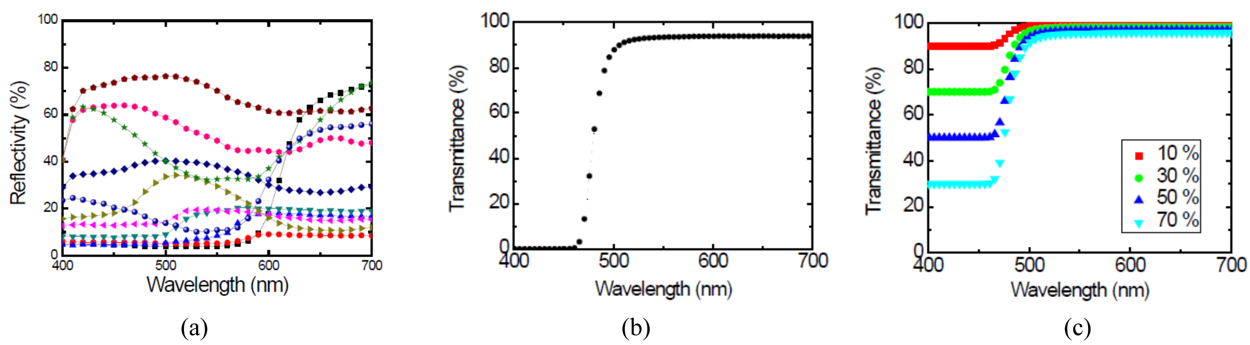


FIG. 3. (a) Reflectivity spectrum vs. wavelength of 10 selected color from 1269 Munsell color. (b) Transmission spectrum vs. wavelength of a commercial Y2 filter from Kenko Co. (c) Modeling of the transmission spectrum according to the wavelengths of 10, 30, 50 and 70% yellow filters.

characteristic of yellow vision. To simulate the degree of yellow vision (x%), the transmission of the yellow filter was added proportionally (Fig. 3(c)),

$$F(\lambda, x\%) = x \times F(\lambda) + 1.0 \times (1.0 - x). \quad (6)$$

This assumption is related to the effective medium theory of electrodynamics, which is a first order approximation of two combined filters. The higher order due to multiple processes was neglected in this first order approximation.

In the next step, to determine the effect of gradual yellow vision, the colors were plotted with different percentages of filter transmittance. From the 1269 Munsell color data, the CIE XYZ and CIE xyY values were calculated under the conditions of the standard illuminant D65 and 10° observer of 1964 CIE [20, 22, 24]. Fig. 4 shows the CIE xyY and CIE LAB values of the 120 selected color data in accordance with the degree of yellow vision, which was calculated using the transmission spectrum function of the yellow filter. In each plot, the colors of the data points represent the Adobe RGB color values calculated using the calibrated monitor function. Fig. 4(a) and 4(b) show the 120 color data with a zero percent yellow filter effect in the xy coordinates (left) and AB coordinates (right). The Munsell color data spans along the color gamut of the CIE xyY and of CIE LAB uniformly with a zero percent yellow filter effect. After applying 50% of the Y2 filter effect, the color space changed significantly as shown in Fig. 4(c) and 4(d). In CIE xyY space, the color space spanned by 120 colors became smaller and severely distorted. In CIE LAB space, the lower part of the color with negative B values, which represents a bluish color, shifted to higher coordinates. This trend became clearer after applying 90% of the yellow filter effect. Fig. 4(e) and 4(f) show the color space of 120 colors with a 90% yellow filter effect. The color space became almost linear (with x+y =1) in CIE xyY space, which can be explained that the Z values of the CIE XYZ tristimulus data representing the blue-like components became almost zero with a Y2 yellow filter. In CIE LAB space, the negative B values represent the blue-like components of the color. The color space after a 90% yellow filter effect was almost positive on the B plane because the colors with negative B values moved to the upper B plane and the colors belonging to the upper B plane shifted from their original positions.

The color difference before and after applying the gradual yellow vision effects were examined. To calculate the color difference, the DE2000 color difference formula with CIE recommendations were used for small color differences, as explained above. After calculating the 1269 × 1269 matrix of the color difference data of the original Munsell colors, the light spectrum was transformed by applying a 10-100% yellow filter, and the 1269 × 1269 color difference matrices (after yellow transformation) were calculated. Using the color difference matrices with each degree of yellow vision, color pairs were selected using the criteria explained in the formula 5. Fig. 5 shows the color difference variation calculated by the function of gradual yellow vision according to the algorithm of two different selection criteria explained in Fig. 2. In Fig. 5(a), the color pairs were selected assuming an 80% of the yellow vision effect. Two colors in each color pair become indistinguishable with a lower boundary constant (α = 2) after applying 80% of the yellow vision effect. Among these pairs, the color pairs, in which the original color differences without yellow vision become larger than 10 (β), were selected. Only 17 pairs out of (1269 × 1268)/2 color pairs fulfilled this requirement. Fig. 5(a) shows the color difference function with the degree of yellow filter for these 17 pairs. The number of color pairs depends strongly on two constants, α and β. Fig. 5(b) show the variations in color difference assuming a 90% yellow vision effect. The two constants, α and β, were set to 2 and 17, respectively. Using these criteria, 3 color pairs were selected as the test color sets, and their color differences were plotted as a function of the yellow vision percentage.

Having developed a color pair selection algorithm and selected the color pairs according to the degree of yellow vision, these concepts and findings were applied to the development of tools for detecting yellow vision. Fig. 6 shows the

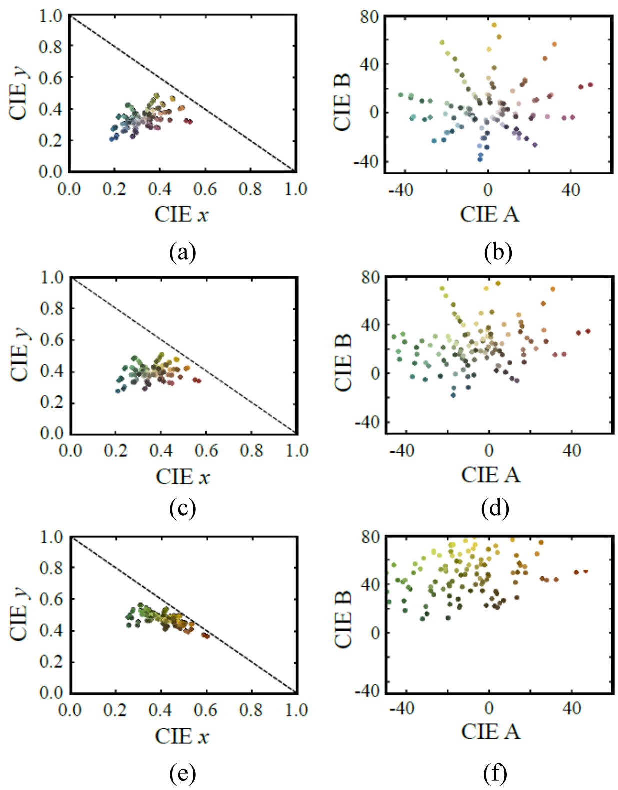
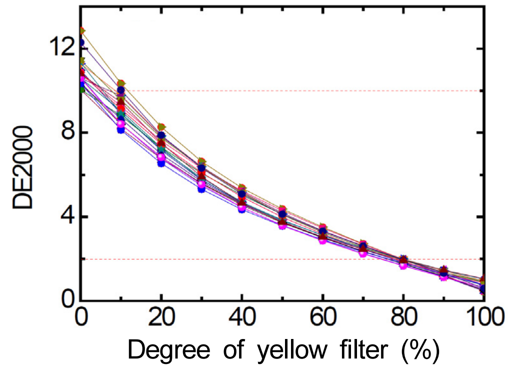
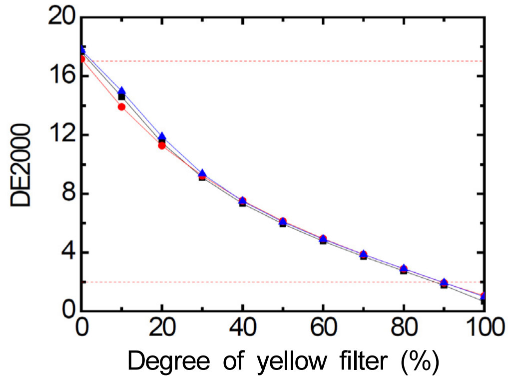


FIG. 4. CIE xyY coordinates of 120 colors from 1269 Munsell color with (a) 0% (c) 50% and (e) 90% yellow filter. CIE LAB (projection to AB plane) values of 120 colors from 1269 Munsell color with (b) 0% (d) 50% and (f) 90% yellow filter. The color of each dot represents the RGB value.



(a)



(b)

FIG. 5. (a) DE2000 vs. degree of yellow filter for the 80% yellow vision test color pairs. The color pairs were selected using the color selection algorithm explained in the text (α and β are 2 and 10). (b) DE2000 vs. degree of yellow filter for the 90% yellow vision test color pairs (α and β are 2 and 17).

color appearance of a selected color pair (a) before and (b) after applying the 90% yellow filter effect. The letter “Happy” can be seen in Fig. 6(a), where two colors have color difference of BYDE2000～17. The letter “Happy” is almost imperceptible after applying a 90% yellow filter effect (Fig. 6(b)), which can be thought as the visual condition of a person with 90% yellow-vision. This method could be applied to produce an Ishihara-like chart of a yellow vision diagnosis caused by an aged lens. Elderly people with yellow vision can be distinguished from those with normal color vision through a test using the pattern charts made with selected color pairs. Depending on the degree of yellow vision, different charts with specific color pairs can be used successfully. Yellow vision test charts can be made with a range of letters, numbers, patterns and animal shapes. On the other hand, the selection of color pairs using this method relies on how the degree of the yellow vision effect is modeled. As explained earlier, the proposed yellow vision model is based on a Y2 yellow filter, and more detailed studies on the spectral characteristics of yellow vision are needed to complete the proposed detection method. The test color pairs were selected from 1269 Munsell colors. The other color databases with known

(a)

(b)

FIG. 6. Color appearance changes in the selected pair (a) before and (b) after application of 90% yellow filter.

spectral reflectivity will be very helpful in choosing more efficient color pairs for a test of yellow vision. Another method to increase the spectral coverage of the test colors can be developed by a spectral reconstruction from the known color database. A recent proposal on the hybrid spectral reconstruction method can be applied easily [25].

IV. CONCLUSION

In this study, a simulation algorithm and a test chart for yellow vision were developed. The spectral changes in yellow vision were modeled successfully based on the transmission data of a Y2 yellow filter, and the change in color appearance caused by the degree of yellow vision was studied. The proposed method of the color appearance change due to yellow vision was based on the spectral change in the light, which could be improved with more realistic data of yellow vision. This method was applied to the 1269 Munsell color data to check the change in color appearance due to the degree of yellow vision. The color differences before and after applying a yellow filter effect were calculated using the CIE DE2000 formula, and compared to select the effective color combinations for a yellow vision diagnosis system. Using this process, the color pairs were selected to construct an Ishihara-like test chart for yellow vision. The proposed method for simulating yellow vision and a yellow vision test chart will be useful for a range of fields in color research, including color image processing and color consistency for the aged.

ACKNOWLEDGMENT

This study was supported by the Convergence Research Grant funded by Pusan National University (PNU, Convergence Research Grant, PNU-2012-0072-0001).

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