Color Compensation Method to Display Images Looking Similar to Their Original Ones for Elderly People

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Abstract—In this paper, we propose a new color compensation method which generates images whose colors are looking similar to their original ones for elderly people. This method is based on a simulation method of color perception by elderly people proposed by Tanaka et al., in which color perception (degradation) by aging is calculated by a simple transformation using 9 coefficients called “effective components”. In the proposed method, we focus on these 9 coefficients and directly adjust (optimize) them so that the color difference between the image perceived by elderly people after color compensation and the original image becomes minimum by using multi-objective evolutionary algorithm called NSGA-II. Simulation result show that for elderly people the output image whose colors are corrected by the proposed method looks very similar to the original ones and the color difference between the output image and the original one is smaller than conventional method.

1. INTRODUCTION

In Japan’s Aging population, they say that 20.3% of men and 25.8% of women are elderly, i.e., about 1/4 of the entire population aged 65 or older based on the statistics of 2010. While aging withers away human physical performance, human visual performance for colors is also deteriorated by aging as well. To understand the change (transition) of human visual performance for colors by aging, a few computer simulation methods that duplicate human color perception have been recently proposed [1],[2]. Tanaka’s simulation method [2] utilizes the actual luminescence emission spectrum measured for the LCD used in the experiments, and relaxes the color constancy hypothesis so that the lenticular yellowing changes not only luminosity but also chromaticity in color perception. Due to these modifications, the results of artificial color perception test using SPP [3] through this simulator remarkably approaches to the results of clinical test comparing with the previous simulator [1]. In Tanaka’s simulation method [2], the colors perceived by elderly people is obtained by a simple transformation using 9 coefficients called “effective component”, each of which represents the contribution from $R, G, B$ signals in $X, Y, Z$ signals.

On the other hand, an image color compensation method that corrects colors in images for elderly people has been proposed [4]. This approach aims to provide better images to be displayed for elderly people because the colors perceived by them are considerably degraded. However, the colors in the image compensated by this method do not necessarily look similar to the ones of original image when the corrected image is degraded through the simulator that duplicates color perception by elderly people [2].

To overcome this problem, in this work, we propose a new color compensation method for images which generates images looking more similar to their original ones for elderly people than the conventional method [4] for establishing barrier-free circumstance for elderly people. In the proposed method, we focus on 9 coefficients called “effective components” in the color transformation process of Tanaka’s simulator [2], and we directly adjust (optimize) these coefficients so that the color difference between the image perceived by elderly people after color compensation and the original image becomes minimum by using a multi-objective evolutionary algorithm called NSGA-II [5]. We verify the performance superiority of the proposed method by comparing with the conventional method [4] through objective and subjective assessment.

2. COLOR REPRESENTATION IN XYZ COLOR SYSTEM

In this work, we define each of tri-stimulus values, $X, Y, Z$, as a combination (summation) of separated $R, G, B$ components by using a translation matrix $\alpha = \alpha_{ij}(i,j = 1,2,3)$ from RGB color system to XYZ color system [6].

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
\alpha_{11} & \alpha_{12} & \alpha_{13} \\
\alpha_{21} & \alpha_{22} & \alpha_{23} \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} =
\begin{bmatrix}
X_R + X_G + X_B \\
Y_R + Y_G + Y_B \\
Z_R + Z_G + Z_B
\end{bmatrix}
(1)
$$
Here, we call \( X_m, Y_m, Z_m (m = R, G, B) \) separated components, each of which means a degree of contribution of \( R, G, B \) signals in each stimulus, \( X, Y, Z \).

On the other hand, each stimulus value, \( X, Y, Z \), can be obtained from the spectral energy distribution as follows:

\[
X = k \sum_{\lambda} S(\lambda) \pi(\lambda) \tau_\lambda
\]

\[
Y = k \sum_{\lambda} S(\lambda) \gamma(\lambda) \tau_\lambda
\]

\[
Z = k \sum_{\lambda} S(\lambda) \tau(\lambda) \tau_\lambda
\]

Here, \( k \) is a constant for normalization, \( S(\lambda) \) is spectral energy of the CIE standard illuminant (D65) at wavelength \( \lambda \), \( \pi(\lambda), \gamma(\lambda), \tau(\lambda) \) are color-matching.

3. SIMULATION METHOD OF COLOR PERCEPTION BY ELDERLY PEOPLE

3.1 Lenticular Yellowning Filter

The simulator proposed by Tanaka et al. employs the two-factor model proposed by Pokorny [7], in which optical density of human lens is described as function of wavelength \( \lambda \) and age \( A \) by

\[
L(\lambda, A) = \begin{cases} 
1.00 + 0.02(A - 32) & (20 \leq A \leq 60) \\
1.56 + 0.0667(A - 60) & (60 \leq A), 
\end{cases}
\]

where \( TL_1(\lambda) \) and \( TL_2(\lambda) \) are two components separated from the total lens transmission function for \( \lambda \) : portion affected by aging after age 20 and portion stable after age 20, respectively [7]. On the other hand, the relationship between input and output spectral intensity \( I(\lambda) \) and \( I'(\lambda) \) at age \( A \) through human lens with an optical density \( D(\lambda, A) \) is given by

\[
D(\lambda, A) = \log_{10} \frac{I(\lambda)}{I'(\lambda)}.
\]

Thus, the transmittance of human lens can be described as

\[
\tau(\lambda, A) = \frac{I'(\lambda)}{I(\lambda)} = 10^{-L(\lambda, A)}.
\]

As shown in Fig. 1, by using this equation we can derive spectral transmission factor of human lens at any age. In [2], we calculate a decreasing rate of spectral transmittance by using two lenticular transmittances for elderly people at age \( A_2 \) and young people at age \( A_1 \) at wavelength \( \lambda \) by

\[
F(\lambda, A_2, A_1) = \frac{10^{-L(\lambda, A_2)}}{10^{-L(\lambda, A_1)}}.
\]

3.2 Missis Filter

Tanaka’s simulator also we employ the retinal illuminance model proposed by Winn [8], in which the pupil diameter at age \( A \) is given by

\[
l(A) = -0.011A + 1.557.
\]

As shown in Fig. 2, the pupil size decreases linearly as a function of age \( A \) at all illuminance level. In [2], we calculate a decreasing rate of retinal illuminance by using two pupil sizes for elderly people at age \( A_2 \) and young people at age \( A_1 \) by

\[
S = l(A_2)/l(A_1).
\]

3.3 Derivation of Effective Components

Since \( F(\lambda, A_2, A_1) \) obtained by Eq.(8) is a transmission factor for the incident light at wavelength \( \lambda \), we cannot directly connect it to \( R, G, B \) signals in the input image. Thus, first we calculate effective component \( K_{(R)}^{(m)}, K_{(G)}^{(m)}, K_{(B)}^{(m)} \), \( K_{(R)}^{(m)}(0 \leq K_{(R)}^{(m)}, K_{(G)}^{(m)}, K_{(B)}^{(m)} \leq 1)(m = X, Y, Z) \) by using \( F(\lambda, A_2, A_1) \) for each stimulus, \( X, Y, Z \), obtained by Eq.(2) ~ (4). Then, we multiply them to separated components \( X_m, Y_m, Z_m (m = R, G, B) \) calculated from each \( R, G, B \) signals in the input image. We assume here that effective component \( K_{(R)}^{(m)}, K_{(G)}^{(m)}, K_{(B)}^{(m)} \) are constant at any age regardless of \( R, G, B \) values.

Now, we explain how to derive effective component. Here, we derive \( K_{(R)}^{(Y)} \) as a representative example. We consider that the spectral transmission factor \( \tau_\lambda \) in Eq.(3) is equivalent to the luminescence emission spectrum \( f_r(\lambda) \) depicted in Fig. 3 when the standard light (D65) penetrates the red filter. That is, we accumulate the spectrum every \( \Delta \lambda \), and obtain the stimulus through the red filter \( Y_r \) for young people at age \( A_1 \) by

\[
Y_r = k \sum_{\lambda} S(\lambda) \gamma(\lambda) f_r(\lambda).
\]

On the other hand, to obtain the stimulus through the red filter \( Y_r' \) for elderly people at age \( A_2 \), we can multiply \( F(\lambda, A_2, A_1) \) to \( f_r(\lambda) \) since the standard light (D65) penetrates not only the red filter but also lenticular yellowing filter. Thus, the tarnished stimulus \( Y_r' \) for elderly people can be derived by

\[
Y_r' = k \sum_{\lambda} S(\lambda) \gamma(\lambda) f_r(\lambda) F(\lambda, A_2, A_1).
\]

Then, we derive effective component as \( K_{(R)}^{(Y)} = Y_r'/Y_r \).

By repeating similar procedure using the green filter \( f_g(\lambda) \) and
4. PROPOSED COLOR COMPENSTION METHOD

4.1 Concept

In the proposed color compensation method, we focus on the color transformation process in Tanaka’s simulator [2]. By using Eq.(1) and Eq.(13), Eq.(14) can be expressed by the following transformation using 9 “effective components” $K^{(X)}_R, K^{(X)}_G, K^{(X)}_B, K^{(Y)}_R, K^{(Y)}_G, K^{(Y)}_B, K^{(Z)}_R, K^{(Z)}_G, K^{(Z)}_B$.

We illustrate the relationship between the color correction by the proposed method and the color degradation through the simulator in Fig. 5. As shown in this figure, here we try to directly adjust (optimize) 9 coefficients corresponding to the above “effective components” so that the color difference between the image perceived by elderly people after color compensation and the original image becomes minimum. In other word, we newly find out another set of 9 coefficients $C = \{c_{11}, c_{12}, c_{13}, c_{21}, \ldots, c_{33}\}$ to properly correct the colors in the input image along the lines of obtaining effective components in the simulator as follows.

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} K^{(X)}_R X + K^{(X)}_G Y + K^{(X)}_B Z \\ K^{(Y)}_R X + K^{(Y)}_G Y + K^{(Y)}_B Z \\ K^{(Z)}_R X + K^{(Z)}_G Y + K^{(Z)}_B Z \end{bmatrix} \times S \quad (15)$$

Note that the pupil reduction factor $S$ in Eq.(14) is included in the color compensation process. We can expect more flexible color correction than the conventional method [4] because the previous method uses only 3 components while the proposed method uses 9 components, which increases the degree of freedom for color correction.

4.2 Optimization Method

In this work, to adjust 9 coefficients in Eq.(16), we employ a multi-objective evolutionary algorithm called NSGA-II [5]. We design an individual as a sequence consisting of 9 real variables in the population, and evaluate each individual using two objective functions described in 4.3.

The flow of NSGA-II is as follows. NSGA-II keeps at the t-th generation a parent population $P_t$ and an offspring population $Q_t$, both of same size $\mu$. The parent population $P_{t+1}$ at the $(t+1)$-th generation is a subset of the best individuals obtained by truncating the combined population of parents and offspring $P_t \cup Q_t$. That is, $P_{t+1} \subset P_t$, where $|P_t| = 2\mu$ and $|P_{t+1}| = \mu$. To obtain $P_{t+1}$, $R_t$ is first classified into non-dominated fronts. The first front $F_1$ contains the best non-dominated solutions $S_1$. The subsequent fronts $F_j, j > 1$, contain lower level non-dominated solutions and are obtained by disregarding solutions corresponding to the previous higher non-dominated fronts, i.e. $F_j, j > 1$, is obtained from the set $R_t - \bigcup_{k=1}^{j-1} S_k$. Once the classification of non-dominated fronts is over, the parent population $P_{t+1}$
Selection of 464 colors

X,Y,Z for each color

Color correction (optimize coefficients)
using $c_{11}, c_{12}, \ldots, c_{13}$

$\tilde{X}, \tilde{Y}, \tilde{Z}$

Perception by elderly people
(Tanaka’s simulator [2])

Minimize color difference

$X,Y,Z$

is filled with solutions belonging to the higher fronts, starting
with front $F_1$. If the whole front $F_i$ does not fit, the required
number of individuals with best crowding distance (CD) are
selected to fill the parent population. Each individual in $P_I$ is
assigned a rank (fitness) equal to its non-domination level (1 is
the best level). Binary tournament selection with crowded
tournament operator, recombination, and mutation operators
are used to create the offspring population $Q_{t+1}$ from $P_{t+1}$.
During selection, solution $x$ wins a tournament if it has a
better rank than $y$. If $x$ and $y$ have the same rank, the solution
with best CD wins. For a detailed description of NSGA-II the
reader can be referred to [5].

4.3 Objective Functions

As the basis of evaluation, we measure the power spectrum
for representative $N$ colors $C_i (i = 1, 2, \cdots, n)$ selected in
xyY color space that can be handled in PC by using a high pre-
cision spectroradiometer. $X, Y, Z$ signals as well as $L^*, a^*, b^*$
signals obtained from the measured spectrum are used as
the basis (original value) for comparison. For these original
signals, we can obtain corrected signals $\tilde{X}, \tilde{Y}, \tilde{Z}$ by Eq.(16)
using a set of coefficients $C = \{c_{11}, c_{12}, c_{13}, c_{21}, \cdots, c_{33}\}$
as well as their degraded ones $\tilde{X}', \tilde{Y}', \tilde{Z}'$. These are transformed
to $L^*a^*b^*$ color space, and the obtained $\tilde{L}^*, \tilde{a}^*, \tilde{b}^*$ are
compared with their original $L^*, a^*, b^*$ signals. Here we calculate
the average MSE (mean squared error) between $\tilde{L}^*, \tilde{a}^*, \tilde{b}^*$
and $L^*, a^*, b^*$ by Eq.(17) for all of representative colors as
the first objective function $f_1$, and its standard deviation as the
second objective function $f_2$, both of which are minimized in
this work by using NSGA-II.

$$\Delta E_i = \sqrt{(L_i^* - \tilde{L}_i^*)^2 + (a_i^* - \tilde{a}_i^*)^2 + (b_i^* - \tilde{b}_i^*)^2} \quad (i = 1, 2, \cdots, n)$$ (17)

$$f_1 = \frac{1}{n} \sum_{i=1}^{n} \Delta E_i$$ (18)
\[
f_2 = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\Delta E_i - \bar{\Delta E})^2}
\]  

(19)

5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Preparation

As described in 4.3, we measured the power spectrum for \( N = 464 \) representative colors, and plotted their positions in \( xyY \) color space in Fig.6. To display these colors, we used “ColorEdge CG245W” produced by NANA Corporation., which can achieve color calibration with high precision. \( L^*, a^*, b^* \) signals of \( N = 464 \) colors are utilized as original signals when we evaluate each individual \( C \) (a set of 9 coefficients) in the population of NSGA-II [5] by comparing the compensated colors using \( C \) perceived by elderly people through the simulator [2]. The genetic parameters for NSGA-II are set as summarized in Table 1.

5.2 Obtained POS

In this work, we try to minimize both the average difference (objective function \( f_1 \) of Eq.(18)) and its standard deviation (objective function \( f_2 \) of Eq.(19)) between the original colors and the corrected ones perceived by elderly people for \( N = 464 \) colors in \( L^*a^*b^* \) color space. That is, we try to solve two-objective minimization problem by NSGA-II. The obtained POS (Pareto Optimal Solutions) are depicted in Fig.7, where we can see a Pareto front forming a trade-off between average difference and its standard deviation, i.e., the solution showing smaller average difference shows larger standard deviation.

5.3 Objective and Subjective Assessment for Output Images

In this work, we selected a solution \( C_{std}^* \) (a set of 9 coefficients \( c_{11}^*, c_{12}^*, c_{13}^*, c_{21}^*, c_{22}^*, c_{23}^*, c_{31}^*, c_{32}^*, c_{33}^* \) for color correction) showing the minimum standard deviation among the obtained Pareto optimal solutions shown in Fig.7. First, we show the average color difference \( f_1 \) and its standard deviation \( f_2 \) achieved by using the coefficients obtained for the ages 60, 70, 80 [4] in Table 2. From these results, we can see that the proposed method achieves very small average color difference with very small standard deviation for \( N = 464 \) colors used in the experiments.

<table>
<thead>
<tr>
<th>age</th>
<th>average color difference ( f_1 )</th>
<th>standard deviation ( f_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.375694</td>
<td>1.02568</td>
</tr>
<tr>
<td>70</td>
<td>0.30023</td>
<td>1.10287</td>
</tr>
<tr>
<td>80</td>
<td>0.378844</td>
<td>1.129704</td>
</tr>
</tbody>
</table>

Next, we compare the output images whose colors are corrected by the proposed method and by the conventional method [4] along with the original image in Fig.8. Also, we show their degraded images perceived by elderly people through the simulator [2] in the same figure. Here, the target age is 80. First, we can see that the image (b) perceived by elderly people through the simulator [2] is considerably degraded (yellowish) by aging compared with the original image (a). Second, in the image (c) whose colors were corrected by the conventional method [4], we can see some white (highlight) regions which is caused by excessive enhancement. On the other hand, the image (d) whose colors were corrected by the proposed method preserves colors in the image. Third, we can see that the image (e) perceived by elderly people [2] after color compensation by the conventional method [4] is clear compared with the degraded image (b), but the colors
are entirely out of alignment from the original image (a). On the other hand, the image (f) perceived by elderly people after color compensation by the proposed method is very close to the original image (a). The average color difference between Fig.8(a) and Fig.8(f) is $\Delta E_{(a)}(f) = 1.508549$, whereas the one between Fig.8(a) and Fig.8(e) is $\Delta E_{(a)}(e) = 23.426887$. From there subjective and objective assessment, we can see that the proposed color compensation method can achieve much better performance than the conventional method[4].

We have conducted experiments for other target ages, and we can see that the proposed method achieves consistently stable performance for any ages showing very small color difference from the original image which should be displayed for elderly people.

6. Conclusions

In this paper, we have proposed a new color compensation method which generates images whose colors are looking similar to their original ones for elderly people. This method focuses on 9 coefficients used in the transformation in Tanaka’s simulator [2] duplicating color perception of elderly people, and directly optimizes them so that the color difference between the image perceived by elderly people after color correction and the original image becomes minimum by using NSGA-II [5]. Simulation results show that the perceived image whose colors were corrected by the proposed method is very close to the original one for elderly people subjectively and objectively.

As future works, we should further analyze output images corrected by using other solutions (sets of coefficients) in POS while we selected one solution among POS to correct color in this paper.

References