A study on chromatic adaptation by the subjective estimation method,

H. Sobagaki, K. Takahama, T. Yamanaka, A. Nishimoto, and Y. Nayaftani


Figure 1.
Spectral power distributions of the fluorescent lamps used. Dashed line with dots corresponds to the fluorescent lamp F8 (4200 K approximately, Ra = 92), and dotted line with crosses to the fluorescent lamp F10 (20000 K approximately, Ra = 71). The chromaticity coordinates are $x = 0.3595$, $y = 0.4657$ for $F_8$, and $x = 0.2214$, $y = 0.2878$ for $F_{10}$. The spectral power distribution of the fluorescent lamp $F_{10}$ was already given in reference [6].

Bild 1.

Ihre Normfarbantipente sind $x = 0.3595$, $y = 0.4657$ für $F_8$ und $x = 0.2214$, $y = 0.2878$ für $F_{10}$.

Die Strahlungsfunktion der Leuchtstofflampe $F_{10}$ ist bereits im früheren Bericht angegeben [6].
Table 3. Transformation matrices $T$ of the empirical chromatic-adaptation equations averaged for observers on the three kinds of test sources: $T_A$ on the source-pair ($F_{65}$, A), $T_{F42}$ on ($F_{65}$, $F_{42}$), and $T_{F200}$ on ($F_{65}$, $F_{200}$)

<table>
<thead>
<tr>
<th></th>
<th>$T_A$</th>
<th></th>
<th>$T_{F42}$</th>
<th></th>
<th>$T_{F200}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.8354</td>
<td>-0.1389</td>
<td>0.5293</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0401</td>
<td>0.9028</td>
<td>0.1752</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>-0.1467</td>
<td>0.3132</td>
<td>2.4976</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9721</td>
<td>-0.1545</td>
<td>0.1578</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1298</td>
<td>0.7625</td>
<td>0.0998</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0424</td>
<td>0.0162</td>
<td>1.2416</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.3675</td>
<td>0.1130</td>
<td>-0.1130</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3350</td>
<td>0.8498</td>
<td>-0.0475</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.0491</td>
<td>0.0875</td>
<td>0.6214</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Transformation matrices $\hat{T}$ of the theoretical chromatic-adaptation equations by use of the fundamental responses in figure 4 and the von Kries theory: $\hat{T}_A$ on the source-pair ($F_{65}$, A), $\hat{T}_{F42}$ on ($F_{65}$, $F_{42}$), and $\hat{T}_{F200}$ on ($F_{65}$, $F_{200}$)

<table>
<thead>
<tr>
<th></th>
<th>$\hat{T}_A$</th>
<th></th>
<th>$\hat{T}_{F42}$</th>
<th></th>
<th>$\hat{T}_{F200}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9277</td>
<td>-0.1158</td>
<td>0.1799</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0261</td>
<td>1.0433</td>
<td>-0.1763</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0628</td>
<td>0.1814</td>
<td>2.2224</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9453</td>
<td>-0.0396</td>
<td>0.0399</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0092</td>
<td>0.9857</td>
<td>-0.0394</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0141</td>
<td>0.0407</td>
<td>1.2459</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1494</td>
<td>0.1661</td>
<td>-0.0457</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0403</td>
<td>0.9756</td>
<td>0.0480</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.0177</td>
<td>-0.0512</td>
<td>0.6886</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Predictability of the three kinds of theoretical chromatic-adaptation equations $\hat{T}_A$, $\hat{T}_{F42}$, and $\hat{T}_{F200}$ assessed by the CIE 1964 color-difference equation

<table>
<thead>
<tr>
<th>Source-pair</th>
<th>For all the used samples</th>
<th>For 8 R8-samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - $F_{65}$</td>
<td>3.24</td>
<td>3.35</td>
</tr>
<tr>
<td>$F_{42}$ - $F_{65}$</td>
<td>3.03</td>
<td>3.70</td>
</tr>
<tr>
<td>$F_{200}$ - $F_{65}$</td>
<td>2.92</td>
<td>2.73</td>
</tr>
</tbody>
</table>

Figure 3
Individual variations of chromatic-adaptation effects for 7 observers on source-pair ($F_{65}$, $F_{200}$), shown on the CIE 1960 (u, v) diagram. See the caption of figure 2 for notations.
In the above analysis we derived the fundamental primaries by the simultaneous use of the two empirical chromatic-adaptation equations. It is also interesting to derive the optimum fundamental primaries for each of the empirical transformation matrices separately. The chromaticity coordinates derived from the average transformation matrix $T_A$ for $(F_{eg}, A)$ are $(x_R, y_R) = (1.2126, -0.2432), (x_g, y_g) = (6.4215, -6.3442)$ and $(x_b, y_b) = (0.1880, -0.0163)$. For $(F_{eg}, F_{200})$ they are $(x_r, y_r) = (0.8194, 0.1811), (x_g, y_g) = (69.2558, -68.4912)$ and $(x_b, y_b) = (0.1408, -0.0329)$. The responses corresponding to these primaries are shown in figure 5 for $(F_{eg}, A)$ and in figure 6 for $(F_{eg}, F_{200})$. The effectiveness of the theoretical chromatic-adaptation equation derived by means of the fundamental primaries for $(F_{eg}, A)$ was good only with regard to the experimental results obtained for the same source-pair, but not so good when used on the source-pair $(F_{eg}, F_{200})$, and vice versa. This suggests that the two sets of fundamental primaries, when based upon only one experimental transformation matrix, are not adequate to predict the chromatic-adaptation effect.

Fig. 5 × Fig. 6 で Interlinkeage Model と chromatic adaptation に関する比較。式において、Interlinkeage Model は、朝日からの色のレベルの変化によると顕著に示した。
§ 2 Interlinkage Model の応用

Analysis of chromatic-adaptation effect by a linkage model

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(Received 22 October 1976)

Hunt suggested that an adaptation-dependent linkage in the visual pathway from the retina to the brain can explain the variation of saturation produced by change of adapting luminance. If variation of saturation is caused by change of linkage, this change must also be involved in chromatic adaptation to light sources that have different chromaticities. By considering the effective adaptation levels of receptors, the model is extended and formulated for application to prediction of chromatic adaptation. It is tested by use of experimental results for chromatic adaptation obtained by Burnham et al. Suitable selection of parameters that specify the state of linkage produces good predictions of the effects of chromatic adaptation.


FIG. 1. Linkage model.

Consider chromatic responses of a test stimulus with tristimulus values \(X, Y, Z\) viewed under an adapting stimulus with tristimulus values \(X_a, Y_a, Z_a\), where the values of \(Y\) and \(Y_a\) are specified in terms of a luminance unit. The tristimulus values \(X, Y, Z\) of the test stim-

ulus are first transformed to values of \(R, G, B\) in the fundamental–primary system \((R, G, B\) system) by

\[
\begin{bmatrix}
X \\
Y \\
Z \\
\end{bmatrix} = M 
\begin{bmatrix}
R \\
G \\
B \\
\end{bmatrix}
\]

(1)

The matrix \(M\) is given by

\[
M = KA^{-1},
\]

(2)

where the matrix \(A\) is constructed from the chromaticity coordinates \((x_r, y_r), (x_g, y_g),\) and \((x_b, y_b)\) of the fundamental primaries \(R, G, B\) by

\[
A = 
\begin{bmatrix}
x_r & x_g & x_b \\
y_r & y_g & y_b \\
x_r & x_g & x_b \\
\end{bmatrix},
\]

(3)

where \(x_r = 1 - x_g - y_g, \nu = r, g, b\). The matrix \(K\) is diagonal

\[
K = 
\begin{bmatrix}
k_1 & 0 & 0 \\
0 & k_2 & 0 \\
0 & 0 & k_3 \\
\end{bmatrix}
\]

(4)

where the elements \(k_1, k_2,\) and \(k_3\) are constants determined by the spectral sensitivities of the fundamental primaries \(R, G, B\).
The tristimulus values \( R, G, B \) in the fundamental-
primary system correspond to the magnitudes of stimuli
incident on the red, green, and blue receptors, respec-
tively. These receptors respond with magnitudes \( R^*,
G^*, B^* \) that correspond to \( R, G, B \), respectively. This
process is assumed to be predicted by the von Kries
law, so that the values of \( R^*, G^*, B^* \) are proportional
to those of \( R, G, B \), respectively. The relation is given by

\[
\begin{bmatrix}
R^* \\
G^* \\
B^*
\end{bmatrix} =
D
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix},
\]

where the proportionality coefficients \( \alpha, \beta, \gamma \) are speci-
ified by the states of adaptation of the three receptors to
the light source under consideration. Each receptor
sends neutral signal with magnitude of \( \alpha, \beta, \gamma \) that
are the same for all receptor types. Generally, it is sus-
ppected that some nonlinear relation exist between \( \alpha, \beta, \gamma \)
and \( R^*, G^*, B^* \). In this study, however, we simply specify

\[
\alpha = R^*, \quad \beta = G^*, \quad \gamma = B^*
\]

as a first approximation.

The signals from each receptor, \( \alpha, \beta, \gamma \) are further transformed
into those of \( \alpha^*, \beta^*, \gamma^* \) after mutual in-
teraction through neural linkages between three kinds of
neural pathways, \( \alpha^*, \beta^*, \gamma^* \) are then trans-
mittted to the brain. The signals \( \alpha^*, \beta^*, \gamma^* \) are postu-
lated to be related linearly to \( \alpha, \beta, \gamma \) by the follow-
ing equation:

\[
\begin{align*}
\alpha^* &= \xi_{11} \alpha + \xi_{12} \beta + \xi_{13} \gamma, \\
\beta^* &= \xi_{21} \alpha + \xi_{22} \beta + \xi_{23} \gamma, \\
\gamma^* &= \xi_{31} \alpha + \xi_{32} \beta + \xi_{33} \gamma,
\end{align*}
\]

or, in matrix representation,

\[
\begin{bmatrix}
\alpha^* \\
\beta^* \\
\gamma^*
\end{bmatrix} = \begin{bmatrix}
\xi_{11} & \xi_{12} & \xi_{13} \\
\xi_{21} & \xi_{22} & \xi_{23} \\
\xi_{31} & \xi_{32} & \xi_{33}
\end{bmatrix}
\begin{bmatrix}
\alpha \\
\beta \\
\gamma
\end{bmatrix},
\]

where \( \Xi \) is a matrix whose \( i, j \) element is \( \xi_{ij} \). The matrix
\( \Xi \) is specified by the state of linkages among three
kinds of neural pathway. The state of linkages depends
upon the effective adapting levels of response mecha-
nisms, which are specified by the tristimulus values
\( R_a, G_a, B_a \) derived from \( X_a, Y_a, Z_a \) by

\[
\begin{bmatrix}
R_a \\
G_a \\
B_a
\end{bmatrix} = M
\begin{bmatrix}
X_a \\
Y_a \\
Z_a
\end{bmatrix},
\]

Now, we consider the dependence of \( \Xi \) upon the tristim-
ulus values \( R_a, G_a, B_a \).

To determine the matrix \( M \), we used the CIE 1931 \( x, y \)
chromaticity coordinates of fundamental primaries
proposed by Judd. These are located at \( x_1 = 0.747, y_1 = 0.253, x_2 = 1.080, y_2 = -0.080, x_3 = 0.171, y_3 = 0.870, \)
We determined matrix \( K \) so that the tristimulus values \( R_1, G_1, B_1 \) in the fundamental-
primary system satisfy the condition \( R_1 = G_1 = B_1 = 1 \) for the adapting source \( B \)
and at the adapting luminance of 0.75 cd/ft^2, which is
designated by the level \( C \) in Hunt's study.

The \( D \) matrix that corresponds to the adaptation at the
matching field, designated by \( D_1 \), is

\[
D_1 = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

The \( D \) matrix that corresponds to adaptation with re-
spect to the test field, designated by \( D_2 \), is

\[
D_2 = \begin{bmatrix}
d_2 & 0 & 0 \\
0 & d_2 & 0 \\
0 & 0 & d_2
\end{bmatrix}
\]

where \( d_2 \) is a constant. The equality of the diagonal
elements suggests that three equal responses \( \alpha^*, \beta^*, \gamma^* \)
will be transmitted to the brain for the reference white
(source \( B \)). Further, we assumed that, at the highest
adaptation level of 100 cd/ft^2 in Hunt's experiment, no
neural linkage exist between the three pathways; that is,
\( \xi(v) \) corresponding to 100 cd/ft^2 is zero.
FIG. 2. Estimated function $\xi$ derived from the experimental results by Hunt. Dots show estimates of $\xi$ at each of the effective adapting levels, designated by A, B, C, D, E, and F, which correspond to the adapting luminance levels used by Hunt. The continuous curve was drawn through these points by a draftsman.

\[
D_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

\[
\Xi_D D_i M = \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} X_{D_G} \\ Y_{D_G} \\ Z_{D_G} \end{bmatrix}
\]

\[
\Xi = \begin{bmatrix} 1 & \xi(10, 6) & \xi(10, 6) \\ \xi(10, 6) & 1 & \xi(10, 6) \\ \xi(10, 6) & \xi(10, 6) & 1 \end{bmatrix}
\]

where $R_{D_A} = G_{D_A} = B_{D_A} = 10.6$, $R_A = 10.8$, $G_A = 9.2$, and $B_A = 3.5$. The values of $\xi$ in the matrices $\Xi$ and $\Xi_\xi$ were taken from Fig. 2.

FIG. 3. Prediction of Hunt's experimental results by use of the linkage model.

\[
\Xi = \begin{bmatrix} 1 & \xi(10, 8) & \xi(10, 8) \\ \xi(9, 2) & 1 & \xi(9, 2) \\ \xi(3, 5) & \xi(3, 5) & 1 \end{bmatrix}
\]

FIG. 4. CIE 1960 $u, v$ chromaticity coordinates of corresponding colors under $D_i$, which give color matches with tristimulus values under source $A$ for the eight test colors specified for use in calculating the general color-rendering index. Open rectangles correspond to the prediction made by the linkage model, where $\xi(10, 6)$, $\xi(10, 8)$, and $\xi(9, 2)$ were set at 0.15, and $\xi(3.5)$ was set at 0.35. Dots correspond to predictions made by use of the von Kries law, and open triangles to those observed by Burnham et al.

FIG. 5. CIE 1960 $u, v$ chromaticity coordinates of corresponding colors under $D_i$, which give color matches with tristimulus values under source $G$ for the eight test colors specified for use in calculating the general color-rendering index. For notation, see caption of Fig. 4, but appropriate values of $\xi$ are used.
Newton Lecture

The third Newton Lecture, delivered by Dr. W. S. Stiles on Thursday, 6 April, glinted like a gemstone in the rich setting of the symposium on Colour Measurement in Industry. Dr. Crawford, Chairman of the Group, when introducing Dr. Stiles, said that he had discovered amongst his students in Edinburgh a widespread impression that the owners of the names attached to a certain physiological effect in vision had long since passed into history—yet the present occasion showed that both the authors of the effect were still active, and he was particularly pleased that it had come about that their two names should again be linked.

Dr. Stiles spoke on Mechanism Concepts in Colour Theory, a theme taken from the content of his forthcoming book, and he illustrated how much of our understanding of the processes of colour vision could be derived from psychophysical measurements. The large lecture theatre of the Physics Department of Imperial College was filled very nearly to capacity, and though perhaps some of us were unable to follow the swift and elegant clarity of Dr. Stiles' exposition with the depth of understanding that it deserved, no doubt we were all inspired by his example in extracting concrete conclusions from some apparently very indirect findings. When Dr. Stiles had concluded, to much applause, Dr. Crawford presented him with a medal engraved to commemorate the event.

Mechanism Concepts
in Colour Theory

W. S. STILES, O.B.E., D.Sc., F.R.S.
\[ a_{14} + 2a_{15}(R_A)^{214} = a_{15} + a_{215}(R_B)^{214} \]
\[ b_{14} + 2a_{15}(G_A)^{214} = b_{15} + b_{215}(G_B)^{214} \]
\[ c_{14} + 2a_{15}(B_A)^{214} = c_{15} + c_{215}(B_B)^{214} \]

Final "red" response = \((1 - \alpha) \log R + \alpha (\log G + \log B)\)

Again, as shown in Fig. 2, the right kind of effect on saturation is reproduced when we put \(\alpha = 0.3\) at the lower level, and \(\alpha = 0\) at the upper. But when we consider the full specifications of the matched stimuli in terms of tristimulus values and not only in terms of chromaticities, the two simple

![Diagram showing chromaticities of matched stimuli exposed in areas A and B, conditioned respectively to high and low levels of white light. Low level: selected chromaticities (Circle points). High level: corresponding chromaticities of the asymmetrically matched stimuli, (1) assuming single-fundamental mechanisms and the power law, \(R = (k R)^0, G = (k G)^0, B = (k B)^0\) (Cross points), (2) assuming multiple-fundamental mechanisms and the law, \(0.7 \log k R + 0.3 \log k G + \log k B + \log R_0 = 0\) plus two similar equations with the roles of the tristimulus values interchanged (Triangle points).]

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§4 Stevens の見解の明示さと MacAdam の Non-linear model のベクトルの関係

![Diagram showing brightness functions for various levels of adaptation. The dashed line shows the terminal brightness locus—the level of sensation reached when the eye comes into full equilibrium with the luminance it is viewing.]

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Brightness Function: Effect of Adaptation
J. C. Stevens and S. S. Stevens
\[ \Psi = R (L - L_0)^{\beta} \]

**Fig. 9.** Chromaticity diagram showing contours of equal \( p \) for the red response in the power form of the nonlinear hypothesis from MacAdam (1956) data. Encircled figures represent the results from Burnham (1952) data.

**Fig. 10.** Chromaticity diagram corresponding to Fig. 9 for the green response.

**Fig. 11.** Chromaticity diagram corresponding to Fig. 9 for the blue response.

MacAdamのベキ指数の順応光依存性

各receptorの実効順応度合いとベキ指数の

関係
Figure 2
§ 6 Non Linear Model と Interlinkage Model の関係

- Hunt 明子と順の実験から、順を基にべキーの回路を求めるべキーの対を求めるべキーの順を表現の寄与を示す。ついての寄与が得られるものである。

- べキーは高級な部分で、1.0 に近いもの。低級な部分ではべキーは 0.5 近く低下。べキーの値のことで物性を総合の寄与に ander 付与の正誤。
  低級な寄与では明白な寄与を示すべキーを正誤する力は分布、寄与寄与を明白に寄与するべキーを示す。

- べキーに関する情報寄与は、暗い寄与の寄与を上昇。
  Non Linear Model と Interlinkage Model の関係？

- Non Linear Model と Interlinkage Model は同じ破壊の盾の両面？
  前者はマクロ、後者はミクロは明確モデル
  変形されると。
図17 自色順で順に輝度変化の場を分か
Non Linear Modelと Interlinkage Modelの
比較の模式図

(A) Interlinkage Model

(B) Non Linear Model

高輝度順

低輝度順

Von Kries
Level

Von Kries
Level

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§7 今後の問題

○ §6 の定式化。既に定形化されていない、その他の定義も使いたい。
検討モデルによる、一致の不一致。

○ 実験
Hue、Lightness は問題なし。
Luminance、Saturation は変更が必要である。

○ Field Test

○ 生活のうつとの対応

○ Opponent-Colors Theory にも適用される理論
K. Roihier
J. Mersan - Hurvich

上の研究との関連。

以上