ANALYSIS OF EQUIVALENT LUMINOUS-EFFICIENCY FUNCTION BY A NEURAL NETWORK MODEL

JingLong WU[1] and Yoshikazu NISHIKAWA[2]

[1] Department of Mechanical Engineering, Faculty of Engineering, Yamaguchi University
[2] Faculty of Information Sciences, Osaka Inst. of Technology

Abstract: In the previous studies, the luminous-efficiency function for the mesopic vision is proposed by several empirical formulas, some discrepancies between the data and the formulation have remained unsolved. In present paper, we propose a model of the equivalent luminous-efficency function based on the brightness perception which covers the scotopic, the mesopic and the photopic conditions. In order to analyse the equivalent luminous-efficiency function, we construct a four layer neural network model. The neural network is composed of three parts: an input layer, two hidden layers and an output layer. This neural network model is trained by the back-propagation learning algorithm with use of training data obtained by psychological experiments. After completion of learning, the response functions of the two hidden units express the scotopic and the photopic coefficients functions which depend nonlinearly on the input light-intensity level. The analysis of the model output indicates that our neural network has acquired an excellent generalization capability. That is, the model of the equivalent luminous-efficiency function has a nice generalization capability in the scotopic, the mesopic and the photopic conditions.

Key Words: equivalent luminous-efficiency function, neural network model, photopic vision, scotopic vision, mesopic vision, brightness photometry system.

1. INTRODUCTION

The human vision system is equipped with two kinds of optic receptor called the rod cells and the cone cells, respectively. The combination of the rod cell and the cone cell functions properly in a very wide range of brightness. At a very high lightness level, called the photopic vision, the cone cells function. On the contrary, at a very low lightness level, called the scotopic vision, the rod cells function. At a middle lightness level, called the mesopic vision, both the rod cells and the cone cells function. The condition of psychological experiments for these three sorts of vision is manifested by the International Commission on Optics (ICO) in 1950 as shown in Table 1.

Spectral sensitivity is one of the fundamental properties of the human vision system. As a standard for it, Commission Internationale de l'Eclairage (CIE) manifested a relative luminous-efficiency function $V(\lambda)$ for the photopic vision and $V'(\lambda)$ for the scotopic vision. In recent studies on the brightness photometry system, only $V(\lambda)$ is used regardless of the lightness level. The problem is on discrepancies between the luminance and the brightness in such brightness photometry system. This problem includes the following two points. First, in the photopic vision, when we see the light or object of the same luminance, the high vivid light has high brightness sensation relative to the low vivid light. Second, in the mesopic vision, as the luminance is getting down, the rod cell begins

Table 1 Conditions of psychological experiment for the scotopic, the mesopic and the photopic visions manifested by the International Commission on Optics (ICO) in 1950.

Brightness Range	Luminance Level	Photometric Fields
Scotopic Vision	0.0001 cd/m²	30 degree
Mesopic Vision	0.05 cd/m²	20 degree
Photopic Vision	100 cd/m²	10 degree

to function instead of the cone cell, and hence the spectral sensitivity shifts from $V(\lambda)$ for the photopic vision to the $V'(\lambda)$ for the scotopic vision. The problem then arises on this brightness photometry system. It must be needed to find for a simple formula to express the mesopic function in terms of the existing $V(\lambda)$ and $V'(\lambda)$ function.

While there have been proposed several empirical formulas[1]~[3], some discrepancies between the data and the formulation have remained unsolved. Recently, several brightness photometry systems based on the brightness perception have been proposed [4]~[7], but these systems are based only on the experimental data of a few observers. Since there exist several individual differences, the brightness photometry system based on data obtained only from a few observers may not fit for others, even if it is tested by the CIE standard illuminant.

In the present study, considering the physiological knowledge, the authors propose a model of the equivalent luminous-efficiency function $V_{eq}(\lambda, I)$, which is a generalization of the luminance-efficiency function in various brightness levels. Hence, $V_{eq}(\lambda, I)$ should become close to $V'(\lambda)$ at the low brightness level and to $V(\lambda)$ at the high brightness level.

The authors propose a model having the following form:

$$V_{eq}(\lambda, I)=F(f_{sc}(I)\,S_{eq\text{-}sc}(\lambda)+f_{ph}(I)\,S_{eq\text{-}ph}(\lambda)) \quad (1)$$

where λ is the wavelength, I is the retinal intensity level, $S_{eq\text{-}sc}(\lambda)$ and $S_{eq\text{-}ph}(\lambda)$ are the equivalent scotopic and photopic luminous-efficiency functions, and f_{sc} and f_{ph} are the scotopic and the photopic coefficient functions depending on the retinal intensity level I, respectively. F is a sigmoid function determined by a neural network. The authors construct the model by using a four-layer neural network, and train it by the backpropagation learning algorithm with use of psychophysical experimental data. It should be noted that the intensity level I appearing e.g. in Eq. (1), contains the luminous-efficiency function in its definition. Hence, Eq. (1) has a difficulty that it is not an explicit form of V_{eq}. In the present study, to avoid this difficulty, the conventional definition of the intensity using $V(\lambda)$ is used.

After completion of learning, the response function of the hidden units, and also the generalization capability of the network for five kinds of CIE standard illuminants are examined.

2. DATA FOR NEURAL NETWORK MODEL

2.1 CIE Standard Illuminant

Whenever object-color stimuli are of main concern, it is desirable to restrict colorimetric measurements and calculations to a few specific and well-defined spectral distributions of radiant power incident on the objects under study. The CIE recommends a set of such spectral radiant power distributions called CIE standard illuminants [8].

The CIE standard illuminant A represents light from the full radiator at the absolute temperature 2856 K. The CIE standard illuminant B is intended to represent direct sunlight correlated with a color temperature at approximately 4807 K. The CIE standard illuminant C is intended to represent average daylight correlated with a color temperature at approximately 6774 K. The CIE standard illuminant D_{65} is intended to represent average natural daylight correlated with a color temperature at approximately 6504 K. For the interest of standardization, CIE recommends that a standard illuminant D_{65} should be used whenever possible. When D_{65} cannot be used, it is recommended either D_{55} or D_{75} should be considered for the application at hand. The illuminants D_{55} and D_{75} correlate with color temperatures at approximately 5503 K and 7504 K, respectively. Those standards are shown in Fig. 1.

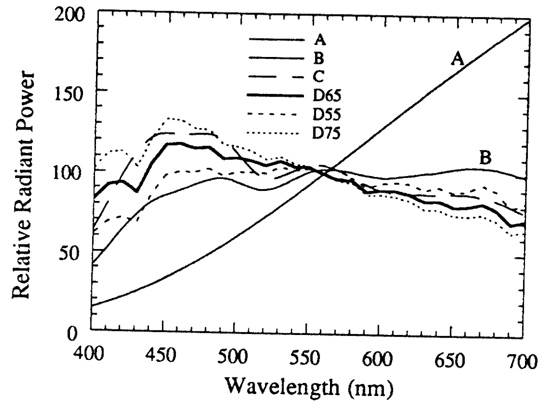

Fig. 1 Relative spectral radiant power distributions of CIE illuminants A, B, C, D_{55}, D_{65} and D_{75}.

2.2 Cell Sensitivity and Adaptation Function

The human has two kinds of optic receptor called the rod cells and the cone cells, respectively. In order to cover the scotopic, the mesopic and the photopic conditions, we must consider the adaptation function of the rod cells and the cone cells.

The spectral sensitivity of the rod cell has been determined for fifty observers by Crawford [9]. In his experiment, the photometric matching method is used at a very low brightness (2.7×10^{-7} cd/m^2) , and a large photometric field (the diameter subtending 20 degrees at the eye) is used. The spectral sensitivities of the cones have been determined by Vos [10]. The spectral sensitivity characteristics of these cells are presented in Fig. 2.

In accordance with the physiological knowledge, a quantitative estimate of the distribution of rods and cones in the human retina has been presented by a function of retinal location[11]. Note that the peak densities for rods and cones are nearly equal, but that the maximum rod density lies well outside the periphery. The decline of the rod density to zero at the fovea is quite steep. The decline of cone density from the exact fovea center is even steeper; beyond about 10 degrees, the density of cones becomes roughly uniform across the retina.

The adaptation of the rod cell has been determined for four observers by Aguilar and Stiles [12]. The test stimulus and field stimulus have 9 and 20 degrees diameter at the eye, respectively. The psychophysical results are used for the adaptation function of the rod, which are presented in Fig. 3.

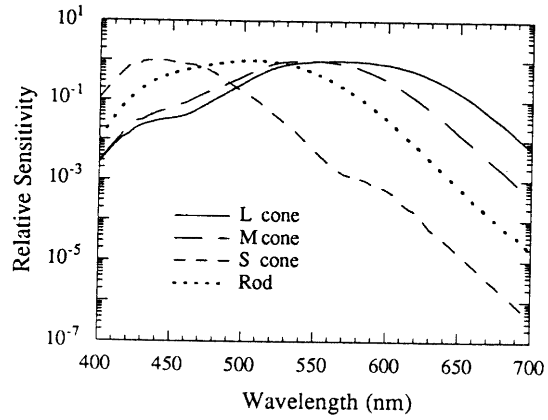

Fig. 2 Spectral sensitivities of the three cones (S, M, L) and rod.

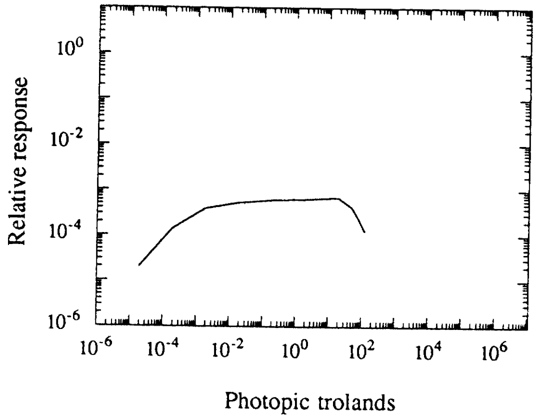

Fig. 3 Response of the rod as a function of the intensity level.

According to Boynton [13], three factors are included in calculations of the cone response: (a) dilation of the pupil, (b) bleaching of the cone photopigments and (c) nonlinearity of the cone response. The pupil area is considered for the data obtained in a psychophysical experiment with the Maxwellian-view. Using the Boynton's equation, the nonlinear response of the cones is determined as follows:

$$C_{ad}(I) = \beta \frac{(IP)^{-0.7}}{(IP)^{-0.7} + 631} \qquad (2)$$

where I represents intensity in the photopic trolands, and β is a scaling constant. The fraction of unbleached pigment P has been calculated by

$$P = \frac{I_0}{I_0 + I} \tag{3}$$

where I_0 is the half bleach constant (taken as 20,000 td) [14]. Equation (2) is illustrated in Fig. 4.

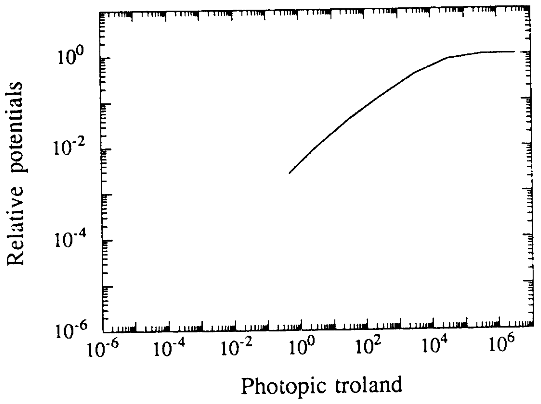

Fig. 4 Response of the cones as a function of the intensity level.

2.3 Luminous-Efficiency Function

For the data of the luminous-efficiency function, the measurement by Sagawa and Takeichi [15] is used. In their experiment, the luminous-efficiency functions have been determined for twenty observers, with nine retinal-illuminance levels of the reference light from 0.01 photopic trolands to 100 photopic trolands (i.e., 0.01, 0.032, 0.1, 0.32, 1, 3.2, 10, 32 or 100 photopic trolands), and with 31 wavelengths covering 400 through 700 nm by 10 nm step. In this experiment, they used the Maxwellian view system, the photometric matching method at 10 degrees photometric field, and a xenon arc lamp as the light source for the reference light. The results have been equated at 570 nm and regularized in between 0 and 1, which are presented in Fig. 5.

3. NEURAL NETWORK MODEL

3.1 Network Structure

The neural network model is composed of three parts: an input layer, two hidden layers and an output layer. For the input layer, relative spectral radiant power distributions of the CIE standard illuminants ***A, B, C, D55, D65*** or ***D75*** is of various illuminance levels are presented in logarithmic scale. The network is required to yield the equivalent luminous-efficiency function in the output layer.

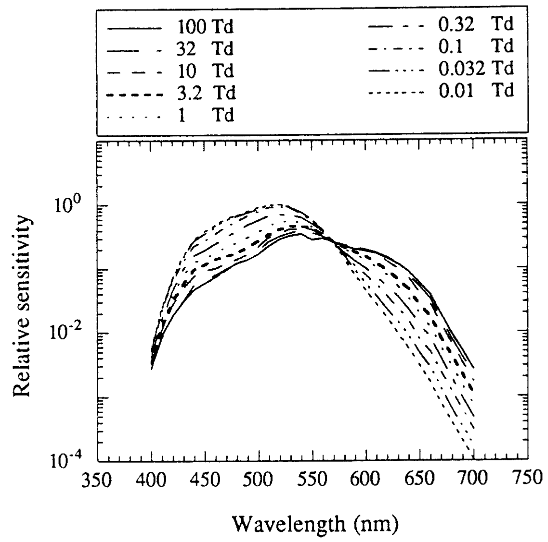

Fig. 5 Luminous-efficiency functions at nine retinal-illuminance levels, from 0.01 to 100 photopic trolands.

Figure 6 shows the neural network model used for the equivalent luminous-efficiency function. Its input layer is composed of four light filters. They correspond to the rod cell and the three types of cone cells (***S, M,*** and ***L***), whose spectral sensitivities are shown in Fig. 2. The output of the four filters on the input layer is then transformed by the adaptation functions. The adaptation function, which is the function of the illuminance level I, of the rod is determined based on the psychophysical data (Shown in Fig. 3), and those of the cones are determined based on the physiological knowledge (Shown in Fig. 4).

There exist two hidden layers 1 and 2. In the hidden layer 1, each unit receives a specified spectral component of the lights from the input layer, i.e.,

$$[Rad(I)R(\lambda)+Cad(I)(S(\lambda)+M(\lambda)+L(\lambda))]Lli(\lambda) \tag{4}$$

where $Lli(\lambda)$ is the radiance of the reference light, $Rad(I)$ and $Cad(I)$ are the adaptation of the rod cells and the cone cells, respectively, and $R(\lambda)$, $S(\lambda)$, $M(\lambda)$ and $L(\lambda)$ are the rod, the S cone, the M cone and the L cone spectral characteristics, respectively. There are 31 units in this layer. These units receive the signal ranging from 400 to 700 nm at intervals of 10 nm.

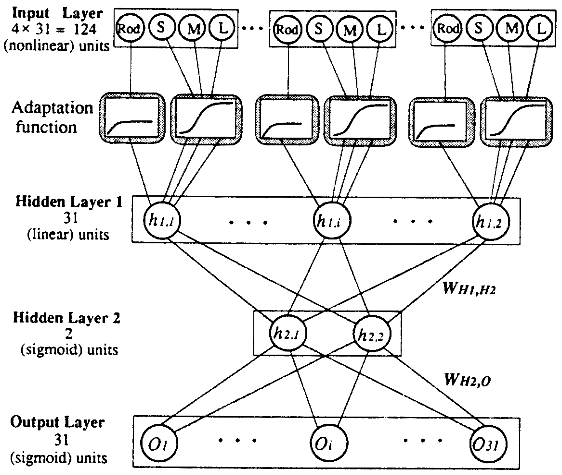

Fig. 6 Structure of the neural network model. $h_{i,j}$ is the j-th unit in the hidden layer i, O_i is the i-th unit in the output layer.

In the hidden layer 2, each unit receives the signal from all the units in the hidden layer 1. In the following analysis, two units are used for this layer; each corresponds to the scotopic coefficient function $f_{sc}(I)$ and the photopic coefficient function $f_{ph}(I)$, respectively. They have the following forms:

$$f_{sc}(I) = F_{sc}\left(\int [R_{ad}(I)R(\lambda)+C_{ad}(I)(S(\lambda)+ M(\lambda)+L(\lambda))]\, W_{H_1,H_2}L_{li}(\lambda)d\lambda \right) \quad (5)$$

$$f_{ph}(I) = F_{ph}\left(\int [R_{ad}(I)R(\lambda)+C_{ad}(I)(S(\lambda)+ M(\lambda)+L(\lambda))]\, W_{H_1,H_2}L_{li}(\lambda)d\lambda \right) \quad (6)$$

The final stage is one output layer with 31 units. This layer stands for the luminous efficiency function at 31 wavelengths ranging from 400 to 700 nm with 10 nm intervals. The formula is given by Eq. (1).

The characteristic of the units in hidden layer 1 is linear. For those of the units in the hidden layer 2 and the output layer, a sigmoid function is used to introduce the nonlinearity of functions F, F_{sc} and F_{ph}.

The connection weights between the hidden layer 1 and the hidden layer 2, W_{H_1,H_2}, and those between the hidden layer 2 and the output layer, $W_{H_2,O}$, are adjusted by learning.

3.2 Learning Method and Training Data

The CIE standard illuminant D_{65} is presented to the input layer of the network at nine intensity levels, and the luminous-efficiency functions measured by Sagawa and Takeichi[15] are presented to the output layer as teacher signals. The luminous-efficiency functions have been equated at 570 nm and normalized in between 0 and 1, with nine retinal-illuminance levels of the reference light from 0.01 to 100 photopic trolands (i.e., 0.01, 0.032, 0.1, 0.32, 1, 3.2, 10, 32 or 100 photopic trolands), and with 31 wavelengths covering 400 through 700 nm by 10 nm step, which are illustrated in Fig. 5.

The neural network model is trained by the backpropagation learning algorithm.

3.3 Results

It is known that the luminous-efficiency function is influenced by the reference light. Considering this finding, the authors examine the validity of the trained network by presenting other CIE standard illuminants.

The responses of the network trained by the CIE standard illuminant D_{65} to the CIE illuminants D_{75}, D_{55}, C, B and A (See Fig. 1) are examined. In order to evaluate the response of the network, the authors introduce the sum of the square of the differences between the output $O_{out}(\lambda)$ and the psychological experiment data $V_{eq}(\lambda)$ relative to the square sum of $V_{eq}(\lambda)$:

$$D(\lambda) = \frac{\sum_{i=1}^{T_{ts}} (O_{out}(\lambda) - V_{eq}(\lambda))^2}{\sum_{i=1}^{T_{ts}} V_{eq}(\lambda)^2} \quad (7)$$

where T_{ts} is the number of input patterns, 9, corresponding to the retinal-illuminance levels. $D(\lambda)$ as a function of the wavelength λ is shown in Fig. 7.

In Fig. 7, except the case of the standard illuminant *A*, $D(\lambda)$ is quite small. This means that the proposed model has a nice generalization capability in the range of the illuminants D_{75}, D_{55}, *C* and *B*. In other words, at least under the present stimulus condition, the model output is not largely influenced by the illuminants D_{75}, D_{55}, *C* and *B*. For the case of the standard illuminant *A*, $D(\lambda)$ gets large around 500 nm while the distribution characteristic of *A* is quite different from other CIE standard illuminants (See Fig. 1).

4. INTERNAL REPRESENTATION IN THE MODEL AND DISCUSSIONS

Let us examine the internal representation obtained by the learning. The output values of the hidden layer 2 are plotted in Fig. 8, where vertical axis indicates the output values, the horizontal axis indicates the intensity level in the photopic troland. They are the averaged results for the test data set D_{75}, D_{55}, *C* and *B*. The hidden units 1 and 2 correspond to the scotopic coefficient function $f_{sc}(I)$ and the photopic one $f_{ph}(I)$, respectively. It is seen that the value of $f_{sc}(I)$ is large in the low intensity area and small in the high intensity area. On the contrary, the value of $f_{ph}(I)$ is small in the low intensity area and large in the high intensity area.

In the low intensity area, i.e., in the scotopic vision, the photopic coefficient function $f_{ph}(I)$ is very small, and the equivalent luminous-efficiency function $V_{eq}(\lambda, I)$ is given approximately by

$$V_{eq}(\lambda, I) = F(f_{sc}(I)\, S_{eq\text{-}sc}(\lambda)) \qquad (8)$$

On the contrary, in the high intensity area, i.e., in the photopic vision, the scotopic coefficient function $f_{sc}(I)$ is very small, and the equivalent luminous-efficiency function $V_{eq}(\lambda, I)$ is given approximately by

$$V_{eq}(\lambda, I) = F(f_{ph}(I)\, S_{eq\text{-}ph}(\lambda)) \qquad (9)$$

In the middle intensity area, i.e., in the mesopic vision, both $f_{sc}(I)$ and $f_{ph}(I)$ are significant. Then $V_{eq}(\lambda, I)$ is calculated by Eq. (1).

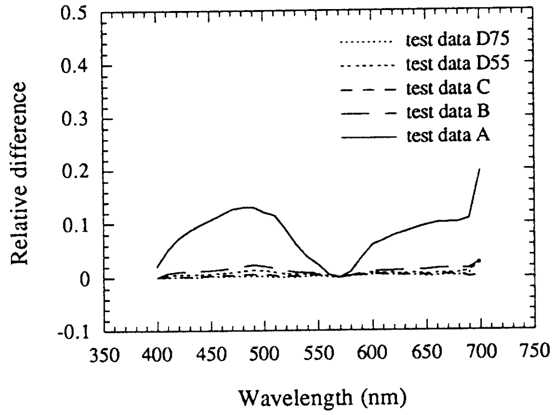

Fig. 7 Relative difference between the model output and the psychological experimental data as a function of the wavelength.

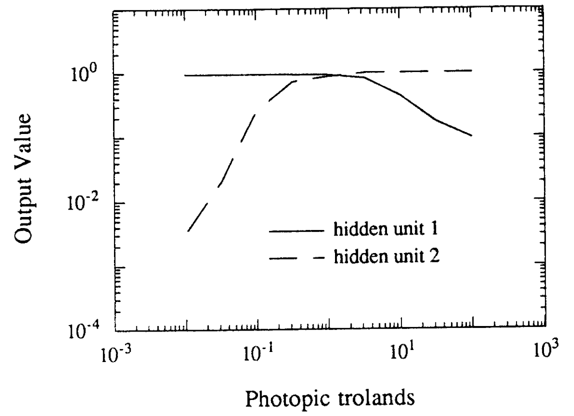

Fig. 8 Output of the hidden layer 2 as a function of the retinal-illuminance levels.

In Nakano's study[16], the scotopic and the photopic coefficient are presented in Fig. 9. The horizontal axis is the intensity level in the photopic trolands. His result is similar to present result qualitatively, while those exists quantitative difference between them. In the scotopic vision range, the scotopic coefficient is very large while the photopic coefficient is small. On the contrary, in the photopic vision range, the scotopic coefficient is very small. In the mesopic vision range, both the scotopic coefficient and the photopic coefficient have significant value.

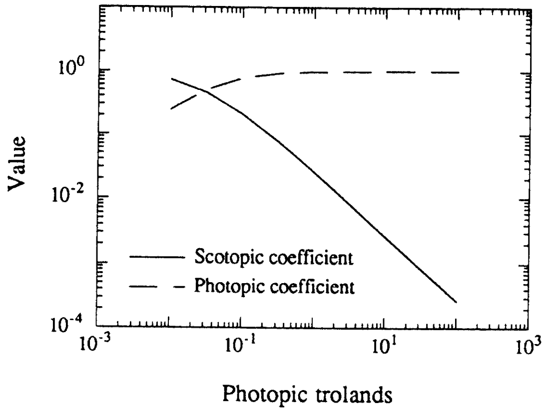

Fig. 9 The scotopic and the photopic coefficients functions of the retinal-illuminance levels.

5. CONCLUSIONS

In the present study, the authors have constructed a four-layer neural network model for the equivalent luminous-efficiency function $V_{eq}(\lambda, I)$ based on the psychological data of brightness perception. In the model, the spectral sensitivity for brightness discrimination of the four types (Rod and S, M, L cones) of photoreceptors, which is derived from a previous psychophysical investigation, is used to describe the response characteristics of the initial input layer. In order to cover the scotopic, the mesopic and the photopic conditions, considering the psychological results and physiological characteristics, the adaptation function of rod and cone cells are also introduced. The model is trained by the backpropagation learning algorithm with use of the psychophysical data to yield the luminance-efficiency function.

The analysis of the model output indicates that our neural network has acquired an excellent generalization capability. That is, the model of the equivalent luminous-efficiency function trained by data in the CIE standard illuminant D_{65} has generalization capability in the other standard illuminants D_{75}, D_{55}, C and B, all in the scotopic, the mesopic and the photopic conditions.

Furthermore, the response functions of the two hidden units which express a nonlinear scotopic coefficients function $f_{sc}(I)$, and the photopic one $f_{ph}(I)$, respectively. In the scotopic vision range, the scotopic coefficient is very large while the photopic coefficient is small. On the contrary, in the photopic vision range, the scotopic coefficient gets very small. In the mesopic vision range, both the scotopic coefficient and the photopic coefficient have significant value.

REFERENCES

[1] Kinney, "Sensitivity of the Eye to Spectral Radiation at Scotopic and Mesopic Intensity Levels," ***J. Opt. Soc. Am.***, **45**, pp. 507--514 (1955).

[2] Kinney, "Comparison of Scotopic, Mesopic and Photopic Spectral Sensitivity Curves," ***J. Opt. Soc. Am.***, **48**, pp. 185--190 (1958).

[3] A. Palmer, "Standard Observer for Large-Field Photometry at any Level," ***J. Opt. Soc. Am.***, 58, pp. 1296--1299 (1968).

[4] S. Stiles, "Further studies of Visual Mechanisms by the Two-Color Threshold Method," ***Coloquio Sobre Problemas Opticos de la Vision***, **1**, pp. 65--103 (1953).

[5] Ikeda and Shimozono, "Mesopic Luminous Efficiency Functions," ***J. Opt. Soc. Am. A.***, **71**, pp. 280--284 (1981).

[6] Yaguchi and M. Ikeda, "Photometric System for Brightness," ***Japan. J. Opt., Kogaku***, **13**, pp. 140--145 (1984, in Japanese).

[7] Nakano and M. Ikeda, "A Model for the Brightness Perception at Mesopic Levels," ***Japan. J. Opt., Kogaku***, **15**, pp. 295--302 (1986, in Japanese).

[8] Wyszeck, W. S. Stiles, "Color Science," Wiley, New York (1982).

[9] Crawford, "The Scotopic Visibility Function," ***Proc, Phys. Soc. Lond.***, **62B**, pp. 321--334 (1949).

[10] J. Vos, "Colormetric and Photometric Properties of a 2° fundamental observer," ***Color Res. Appl.***, **3**, pp. 125--128 (1978).

[11] N. Cornsweet, "Visual Perception," Academic Press, New York (1970).

[12] Aguilar and W. S. Stiles, "Saturation of the rod Mechanism of the Retina at High Levels of Stimulation," ***Optica Acta***, **1**, pp. 59--65 (1954).

[13] M. Roynton, "Human Color Vision," Holt, Rinehart and Winston, New York (1979).

[14] H. Rushton and G. H. Henry, "Bleaching and Regeneration of Cone Pigments in Man," ***Vision Res.***, **8**, pp. 617--631 (1968).

[15] Sagawa and K. Takeichi, ***Proc. 20 th Session CIE***, **D103** (1983).

[16] Abramov and J. Gordon, "Color Vision in the Peripheral Retina. I. Spectral Sensitivity," ***J. Opt. Soc. Am.***, **67**, pp. 195--202 (1977).

[17] Nakano, "Proposal of a Brightness Photometry System Based on the Human Vision," ***Proceedings of the 8th Joint Conference on Color Technology***, pp. 103--106 (1991, in Japanese).

(Received April 15, 1997)

ニューラルネットワークモデルによる等価比視感度関数の解析

呉 景龍 [1]　　西川 禕一 [2]

[1] 山口大学 工学部 機械工学科
[2] 大阪工業大学 情報科学部

論文概要： 従来の研究では，薄明視の比視感度関数が経験式により計算され，実データと経験式との不一致の問題が存在している．本研究では，我々は心理的な明るさ知覚に基づいて，暗所視，薄明視および明所視の領域を考慮した等価比視感度関数を提案している．このような等価比視感度関数を解析するため，我々は４層ニューラルネットワークを構築する．構築されたニューラルネットワークは１つの入力層，２つの中間層および１つの出力層の３つの部分によって構成される．心理学実験より得られた比視感度関数のデータを教師信号として，バックプロパゲーション法によってニューラルネットワークを学習させる．学習後のニューラルネットワークの中間層における内部表現について検討した．２個の中間層ユニットの出力には暗所視の寄与率関数と明所視の寄与率関数とに対応するものが得られており，これらは入力光の強度の変化に伴って非線形的に変化する．ニューラルネットワークの出力の解析より本ネットワークモデルの汎化性が高いことは確認された．すなわち，本研究によって提案された等価比視感度関数モデルは暗所視，薄明視および明所視の領域において汎用性が高いものであると考えられる．