Multilayered Neural Network Models for Color Blindness

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Abstract

Multilayered neural network models for normal and dichromatic color vision, which realize mapping from cone space into perceived color space by back-propagation learning, were constructed. After learning was completed, the properties of each model acquired by learning, such as spectral response property, hue representation of spectral light and wavelength discrimination, were examined. Each model predicted the experimental evidence well enough to understand the mechanism.

Introduction

Color blindness is a consequence of the loss of some types of cones, and the nature of color blindness has been studied through psychophysical experiments and/or predicted by color vision models[1][2][3]. In this study, nonlinear mapping from cone space, defined by responses of cones, into perceived color space, defined by responses of one luminance and two chromatic responses, was generated by multilayered neural networks. The networks were trained using Munsell color chips as training color stimuli which cover most of the perceived colors.

After learning was completed, the network properties acquired by learning were analyzed using the spectral lights as testing color stimuli, and the results were compared with the psychophysical evidence. Futhermore, introducing the hypothesis that "dichromatic color vision has the best color discrimination ability under the constraint of the loss of one type of cones," we constructed the models for dichromatic color vision. The color representation of the dichromatic color vision was estimated through analysis of the dichromatic color vision models.

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Network structure and learning data

Figure 1 shows the structure of the network and learning data. Spectral energy distribution of light, I(λ), is the input to the network (Fig.1(a)) and is given as a product of the spectral energy distribution of the illuminant, E(λ), and the spectral surface reflectance, R(λ). We used the measured surface spectra of Munsell chips as R(λ) sampled at 81 wavelengths from 380 to 780nm at 5nm intervals, and used the spectral energy distribution of the CIE illuminant C as E(λ).

Connecting weights between the input layer and second layer were fixed to the spectral sensitivities of cones proposed by Smith and Pokorny[4] (Fig.1(b)). Thus, these three units correspond to the three types of cones (L, M and S cone units). Teaching data consist of the coordinates of each color chip in the Munsell color space, which are transformed from the original cylindrical system into the orthogonal system and normalized as shown in Fig.1(c). That is, each unit represents lightness, redness or greenness, or blueness or yellowness, of the input color chips.

Dichromatic color vision is represented by eliminating one of the three units in the second layer. Protanopia, deuteranopia and tritanopia are each represented by a loss of one of the L, M or S cone units, respectively. That is, each model has only two cone units in the second layer. Each dichromatic color blindness model is trained by the same learning data as a normal color vision model under such structural constraints. Then, these models are expected to acquire the best color discrimination ability under the constraint.

We randomly divided the 1569 input–teaching data into a 640 learning-data set and a 929 test-data set, and trained each network by the back-propagation learning method which minimizes the output error.

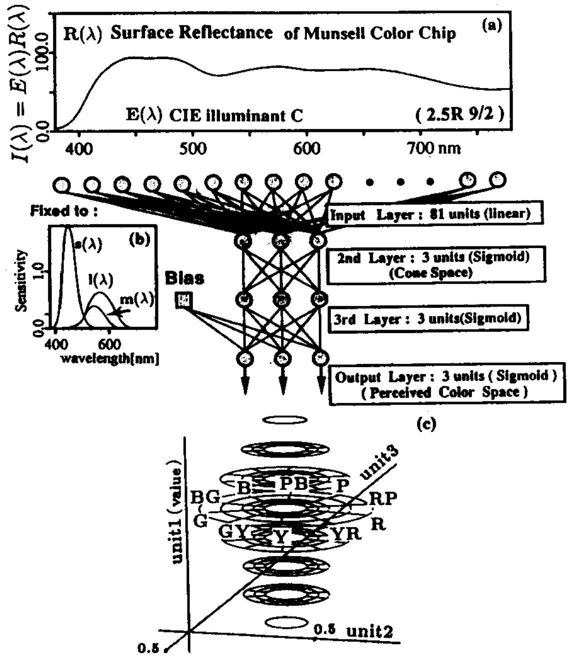

Fig.1. *Network structure and learning data. Each layer consists of 81, 3, 3 and 3 units, and connecting weights between input layer and second layer were fixed to the spectral sensitivities of three types of cones (b). (a) Spectral energy distribution of light from each Munsell color chip is the input data. (c) The network is trained to output the coordintes of perceived color space for each Munsell color chip, which represent lightness, redness or greenness, and blueness or yellowness.*

Analysis of the network

After learning was completed, we analyzed the network response to spectral light stimuli, which are often used as color stimuli to measure the characteristics of color vision, such as the spectral response property or wavelength discrimination property.

Spectral response and hue representation

Figure 2 shows spectral responses of each unit and $\theta(\lambda)$ of the normal color vision model. Spectral responses (Fig.2(a)) of unit 1, unit 2 and unit 3 are monophasic, triphasic and biphasic, respectively, and these are characteristics similar to the luminous efficiency curve and color opponent responses. The hue angle of spectral light stimuli is given by

$$\theta(\lambda) = \tan^{-1} \frac{R_3(\lambda) - 0.5}{R_2(\lambda) - 0.5} \quad , \tag{1}$$

where $R_2(\lambda)$ and $R_3(\lambda)$ are spectral responses of unit 2 and unit 3, respectively. $\theta(\lambda)$ of the normal color vision model (Fig.2(b)) accounts well for the color appearance, such that there is no purple in the spectrum.

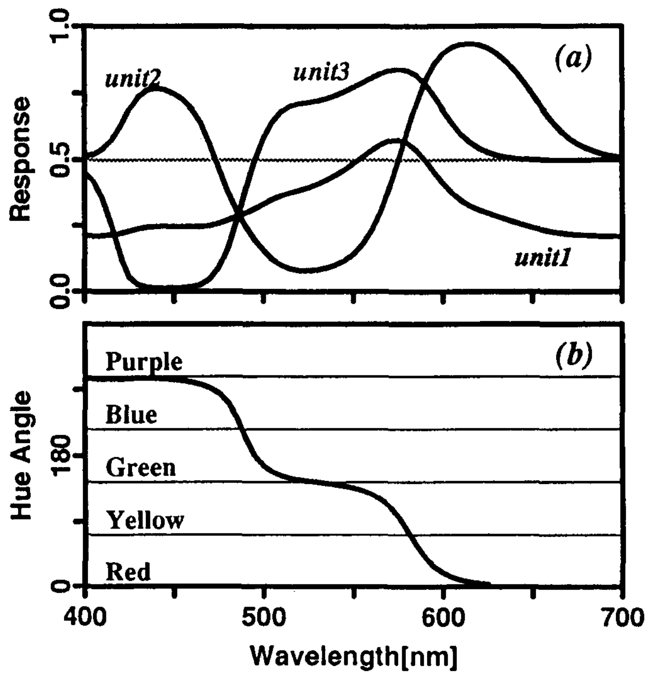

Fig.2. *Spectral response and hue representation for spectral light of normal color vision: (a) spectral response of each unit of normal color vision model, (b) $\theta(\lambda)$ as the hue representation.*

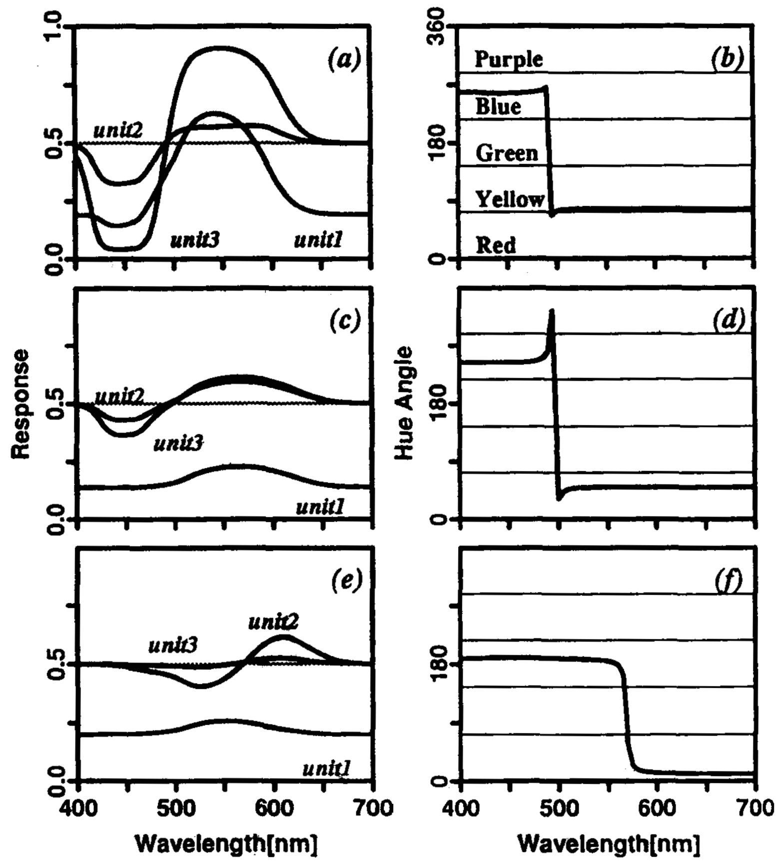

Fig.3. *Spectral response and hue repsresentations for (a)(b) protanopia, (c)(d) dueteranopia and (e)(f) tritanopia.*

Figure 3 shows spectral responses and $\theta(\lambda)$ of each dichromatic color vision model. It is known that in the case of dichromatic color blindness, the spectrum can evoke only two hue sensations, yellow–blue for protanopia and deuteranopia, and green–red for tritanopia dichromat. The spectral responses and $\theta(\lambda)$ shown in Figs.3(b),(d),(f) agree with such observations, and this result suggests that hues which are perceived by protanopia and deuteranopia dichromats are slightly different.

Wavelength Discrimination

Wavelength discrimination, which is the wavelength difference necessary to produce a barely noticeable difference, has been measured in psychophysical experiments to evaluate the way the visual system performs. For normal color vision[5], there are two minimal points where the discrimination is best (470nm and 580nm), and that discrimination is relatively poorer both in the midspectral region and at the spectral extremes, as shown in Fig.4(a).

To calculate the wavelength discrimination for the models, we defined it $\Delta\lambda$ as follows:

$$\Delta\lambda = \left|\frac{d\theta}{d\lambda}\right|^{-1} \tag{2}$$

Wavelength discrimination of the model for normal color vision (Fig.4(b)) shows a similar general trend; we can see the best discrimination at 470nm and 570nm.

Wavelength discrimination for each dichromatic color blindness was also measured,[6][7] as shown in Figs.5(a),(b). Each dichromatic model (Figs.5(c),(d)) well fit the experimental wavelength discrimination data, as well as the normal color vision.

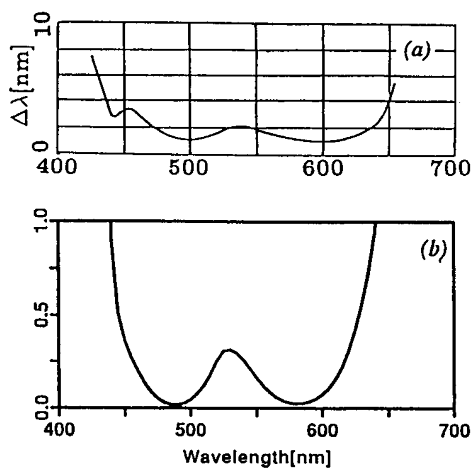

Fig.4. *Wavelength discrimination of nomal color vision. (a) psychophysical experiment*[5]*, (b) neural network model.*

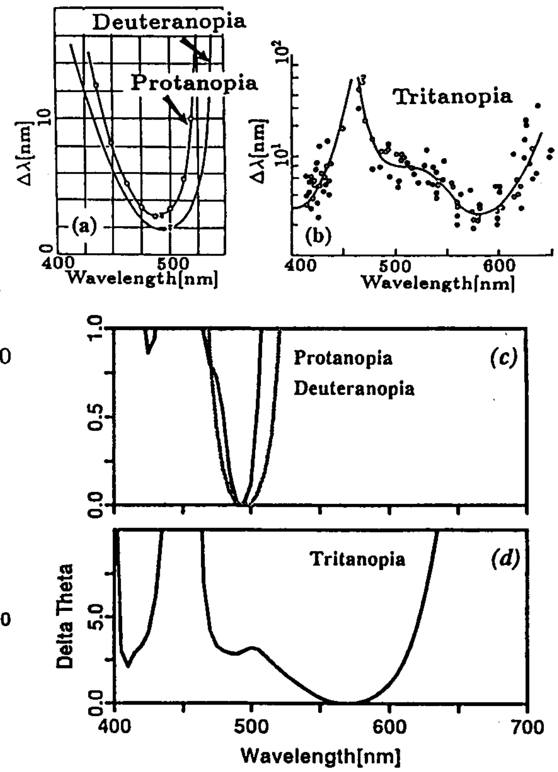

Fig.5. *Wavelength discrimination for dichromatic color vision: psychophysical experiment for (a) protanopia and deuteranopia*[6]*, (b) tritanopia*[7]*; results of the model for (c) protanopia and dueteranopia, (d) tritanopia.*

Conclusions

The neural network models for normal and dichromatic color vision, which realize mapping from cone space into perceived color space, were constructed, and it was shown that the properties of the networks acquired by learning accounted well for the nature of each color vision, such as hue representation, wavelength discrimination property of each dichromatic color vision in the perceived color space. These results suggest that the hypothesis for constructing the dichromatic color vision models is acceptable and also suggest that colors are represented in the visual system by lightness and opposing color responses, that is, redness or greenness and blueness or yellowness, which was predicted in our previous investigation of the analysis of surface reflectance of Munsell color chips[8].

References

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