人間の視覚系における明るさチャンネルの並列性について*

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On a Parallel Structure of the Achromatic Channel in the Human Visual System*

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The human visual system is a sensory organ having a very high performance. It analyzes various visual information at a very high speed. The key of such performance will be the parallel structure of the visual system. As the fundamental process of the human visual system, the authors pay attention to the achromatic information processing system. In order to elucidate mechanism of the achromatic channel, in the present paper, the achromatic perception has been measured by three psychological experiments. In the first experiment, the spatial characteristic of the achromatic perception has been measured for six wavelengths of monochromatic light. In the second experiment, the relative spectral sensitivity of the achromatic perception has been measured for two test sizes. In the third experiment, the relative spectral sensitivity of the achromatic perception has been measured for two background levels, i.e., at 55 and 798 Td. It is difficult to explain the experimental results by the conventional achromatic channel model, and the experimental results suggest that the achromatic information is processed by several subsystems in parallel. In order to explain the experimental results, we propose a model of achromatic information processing composed of five stages and three subsystems.

1. Introduction

The human visual system has been evolving for long time and has attained very high performance as a sensory organ. If the mechanism of human visual system is elucidated, the findings will contribute to technology of image processing, pattern recognition, robotic vision etc. In the human visual system, input information is processed as follows: the light is caught by the eyes and transduced to electrical signal in the retinas. Then, it is sent to the brain, where the information is analyzed in various ways, e.g., achromatic and chromatic information, three dimensional depth, texture, motion and form. To pay attention to the achromatic and chromatic information processing, one of the fundamental processes of the human vision, it has often been claimed that the visual system involves three channels in early stages of the processing^{1)~6)}. These channels are termed a red-green channel, a yellow-blue channel, and an achromatic channel, respectively. It is supposed that the former two channels deal with chromatic information and contribute to the chromatic perception, while the third one is specialized for achromatic information processing and serves the achromatic perception. In previous psychological investigations, the achromatic channel has been considered as a single one presented by a linear sum of the output of the two sorts of photoreceptor in the retina, i.e., M and L cones based on their spectral sensitivities^{2), 7), 8)}.

However, in the several measurements^{9), 10)}, the results suggest that the luminous-efficiency

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function[†] depends on the stimulus size. In other words, the spatial characteristic of achromatic perception depends on the wavelength of stimulus. Furthermore, it is known that as a physiological knowledge, the ganglion cells in the retina of monkey are classified into several types by their receptive fields^{11)~13)}. Considering these psychological experimental results and the physiological structure, we propose a hypothesis that the achromatic channel is constituted by parallel subsystems.

In order to determine the mechanism of the achromatic channel based on this hypothesis, we measure the spatial characteristics and the spectral sensitivities of the achromatic perception. In the first experiment (Experiment 1), the spatial characteristics of achromatic perception for six wavelengths of monochromatic light are measured. The results show that there exists

strong dependency of the spatial characteristic on the wavelength of stimulus. In the second experiment (Experiment 2), the relative spectral sensitivity of the achromatic perception has been measured for two test sizes at the background level of 210 Td^{††}. In the third experiment (Experiment 3), the relative spectral sensitivity of the achromatic perception has been measured for the two background levels of 55 and 798 Td. The conventional single achromatic channel model has difficulty in explaining the obtained experimental results. In other words, it suggests that the achromatic information may be processed by several parallel subsystems if we assume each subsystem has a simple structure. In order to explain the experimental results, we propose an achromatic perception model consisting of three subsystems working in parallel.

2. Methods of Psychological Experiment

2.1 Apparatus

For psychological experiments to measure the spatial characteristic and spectral sensitivity of the achromatic channel, a three-channel, computer-controlled, Maxwellian-view optical system (see Fig. 1) has been developed. Three beams are derived from three light sources, each of which is a lamp with a halogen tungsten filament. Each beam is rendered monochromatic by a monochromator (Jovan Ivon, H20 VIS), whose half-bandwidth is set to 4 nm. Channel 1 provides background stimuli through the background-APerture (APb). Channel 2 provides test stimuli through the test-APerture (APt). The focus of the test-aperture is adjusted by a remote controlled motor. Channel 3 provides fixation point stimuli through the fixation-APerture (APf). The three beams are combined and presented in the Maxwellian-view through a 2 mm-diameter Artificial Pupil (AP). All lenses are achromatic doublets and mirrors are front surfaced. The intensity of each monochromatic light is controlled by adjusting the neutral density filters and the voltage supplied to the lamps with the aid of a personal computer (NEC PC-9801). The observer's head position is fixed by a dental

M1-M3: monochromators, ND1-ND3: neutral-density filters, APb: background-aperture, APt: test-aperture, S: shutter, APf: fixation-aperture, BM1 and BM2: beam splitters, MR: mirror, AP: artificial pupil.

Fig. 1 Schematic diagram of the experimental system

[†] The luminous-efficiency function is the spectral sensitivity of luminous sensation, which is one of the fundamental properties of the human visual system. As its standard, Commission Internationale de l'Eclairage (CIE) manifested a relative luminous-efficiency function.

^{††} Td is the unit of retinal illuminance. 1 Td implies that the surface of 1 cd/m² is seen by the pupil area with 1 mm².

these measurements, the retinal illuminance of the stimuli is controlled by a personal computer.

(3) Calibration of the Neutral Density Filters

The neutral density filters are calibrated for spectral transmission by using the International Light Photometer. The results of these measurements are stored in the memory of the personal computer to control the intensity of the test monochromatic beams.

(4) Calibration of the Chromatic Aberration

In order to exclude the chromatic aberration of the lenses, the focus of each test pattern is controlled by the observer at the beginning of each measurement with use of the remote controller.

2.4 Observers

Two males are observers. They are confirmed to have normal color visions as defined by the Nagel anomaloscope using the Ishihara pseudoisochromatic plates, and the Farnsworth-Munsell 100-hue test. They are also endowed with normal acuities.

2.5 Procedure

The threshold of the achromatic perception is determined by the double random staircase procedure¹⁴⁾. In this procedure, stimuli are taken from two independent staircases randomly intermixed, in order to prevent the observer from anticipating the next contrast of adjustable test pattern presented. One of the pair of staircases starts from the intensity at which the test stimulus is obviously visible (i.e. the staircase H). Another staircase starts from the intensity at which the test stimulus is obviously invisible (i.e. staircase L). On each trial, the observer is forced to make a binary decision whether the test stimulus is seen or not. Each staircase follows independently the same rule of the step size. That is, a "seen" response is followed by a constant decrement in the intensity of light, while a "not seen" response is followed by a constant increment. In each staircase, the initial step size is set to 1/10 of the difference between the two starting intensities, and after the first reversal of the response, the step size is set to the half of the initial step size. Each staircase is terminated when four reversals are made. The last six reversal points from each pair of the staircases are used as measurements. They are averaged to give a daily mean. At least three daily means are measured, and they are averaged to give an overall mean for each condition.

The experimental procedure is summarized as follows:

(1) Dark Adaptation

The observer is kept in a dark room for 6 minutes to adapt to a dark condition.

(2) Calibration of the Chromatic Aberration

The observer adjusts the focus of the test pattern by using the remote controller to exclude the chromatic aberration.

(3) Light Adaptation

The observer is exposed to a given background illuminance for 6 minutes for adaptation.

(4) Predetermining Starting Points

Two starting points for the double random staircase procedure are predetermined by the method of adjustment. The first stimulus is a test stimulus of arbitrary intensity. The observer makes a response whether the stimulus is seen or not. If the observer says "yes" (he can see it), the next stimulus is made less intense, and if the observer says "no" (he can not see it), the second stimulus is made more intense. In this way, the starting point of the staircases H is determined by the intensity at which the test stimulus is obviously visible. In a similar way, the starting point of the staircases L is determined by the intensity at which the test stimulus is obviously invisible.

(5) Determining Threshold

The thresholds are determined by the double random staircase procedure.

3. Spatial Characteristic of the Achromatic Perception (Experiment 1)

3.1 Results

Results obtained by the two observers are shown in Fig. 5. Fig. 5 (a) and 5 (b) are the results by the observers JW and YE, respectively. Every point indicates the average of 6 measurements. The ordinate shows the relative threshold of the achromatic perception, and the abscissa shows the test diameter. The results have been equated at 5.3 min, and normalized in between 0 and 1.

From Fig. 5, it can be seen that in all the wavelength the thresholds decrease as the size of the test stimulus increases. Based on the theory of spatial summation¹⁵⁾, the threshold is determined by the energy of the test stimulus, and hence, its intensity at the threshold decreases $1/m$ times if its area increases m times. The remarkable feature of the obtained results is the difference among the curve inclinations by the wavelength of stimulus. The inclination represents the magnitude of the effect of spatial summation. The relative inclinations of the curves by the two

Wavelength of the test is identical to that of the background. Each datum point is the average of 6 measurements for the observer. The test pattern is presented with 500 msec duration. The background illuminance is 210 Td. Vertical bars indicate the standard deviations.

Fig. 5 Threshold of the achromatic perception as a function of the spatial size of the test pattern for six wavelengths of monochromatic light

Table 1 Relative inclinations of the spatial summation curves

Wavelength	450 nm	505 nm	540 nm	570 nm	630 nm	670 nm
$S_{JW}^*(\lambda)$	2.1	1.4	1.0	1.2	1.4	1.8
$S_{YE}^*(\lambda)$	1.8	1.5	1.0	1.1	1.3	1.7

(Note: * The value indicates the inclination of each oblique line fitted to the experimental result by the least square method. All the values are normalized by the value at the wavelength of 540 nm.)

observers are shown in Table 1. The inclination at the wavelength of 540 nm is normalized to 1. Table 1 shows that the inclinations attain their minima at 540 nm, get larger in both ranges of

(a) Receptive field function

(b) Experimental stimuli

(c) Relative threshold as a function of the stimulus area

Fig. 6 Explaining the threshold of the achromatic perception in Experiment 1 based on the receptive field function

longer and shorter wavelength, and attain their maxima at 450 nm.

3.2 Discussion

The experimental results show that the effect of spatial summation depends on the wavelength of light. It can be explained by a structure of the receptive field depending on the wavelength. If we assume that the threshold can be determined by the magnitude of an excited cell (see Fig. 6(a)), the threshold can be given by the following:

$$L_{th} = \frac{1}{K \int_0^{r_0} r \Psi(h, r) dr} \quad (1)$$

where L_{th} is the threshold of the achromatic perception, r_0 is the radius of test stimulus, h is a parameter representing the size of the receptive field, and K is a constant. $\Psi(h, r)$ is the Receptive Field Function (RFF) that was proposed by Blackwell¹⁶⁾. In Blackwell's study, $\Psi(h, r)$ is determined by experimental data as an empirical smooth curve. In order to explaining the experimental results qualitatively, we assume the RFF¹⁷⁾ as follows:

$$\Psi(h, r) = e^{\frac{-r^k}{h}} + b \quad (2)$$

where k and b are constants. Fig. 6 is the threshold of the achromatic perception obtained by eqs. (1) and (2). In eq. (1). When the diameter of

the test stimulus is larger than the size of the receptive field parameterized by h , the marginal contribution $r_0\psi(h, r_0)$ to the integration in eq. (1) gets small, and decrease in the threshold gets small according to increase in the size of test stimulus. Hence, the curve inclination of the spatial summation is small (see Fig. 6(c)). On the other hand, when the diameter of the test stimulus is smaller than the receptive field, the threshold decreases largely according to increase in the diameter of the test stimulus. Namely, the steep inclination means that the area of spatial summation is large. The experimental results are explained by the above theory as follows: in the short and long wavelength ranges, the receptive field and the spatial summation are large, and in the middle wavelength range, the receptive field and the spatial summation is small. It is difficult to explain this phenomenon by the conventional single achromatic channel model. That is, we must consider the characteristics of the achromatic perception differently in short-, middle- and long-wavelength ranges. If we assume that the achromatic information is processed by parallel subsystems whose spacial characteristics are fixed, at least three subsystems for the three wavelength ranges are needed to explain the obtained results.

4. Spectral Sensitivity of the Achromatic Perception (Experiment 2, 3)

4.1 Results

Fig. 7 (a) and (b) illustrate the results obtained by using the test sizes of 5.3 and 45.6 min, respectively. They are shown by the sensitivity of the achromatic perception, i.e., the inverse of the threshold, as a function of the wavelength. In Fig. 7, the solid curves indicate the predictions by our model proposed later. Each datum point is the average of 6 measurements for an observer. The ordinate shows the relative sensitivity normalized at 570 nm, and the abscissa shows the wavelength of the stimulus. In Experiment 2, the background illuminance level is set at 210 Td. The results of the observers JW and YE are shown by the circles (open circles for the test size of 5.3 min,

and solid circles for 45.6 min) and the squares (open squares for the test size of 5.3 min and solid squares for 45.6 min), respectively. In Experiment 3, the background illuminance levels are set at 55 Td (open triangle for the test size of

(a) Relative sensitivity for test size 5.3 min

(b) Relative sensitivity for test size 45.6 min

(c) Comparison of the model prediction between the test sizes 5.3 min and 45.6 min

Wavelength of the test is identical to that of the background.
Each datum point is the average of 6 measurements.

Fig. 7 Relative sensitivity of the achromatic perception as a function of the wavelength for the two test patterns and the three retinal illuminance levels

5.3 min and solid triangle for 45.6 min) and 798 Td (open diamond for 5.3 min and solid diamond for 45.6 min).

From Fig. 7, it can be seen that there exists a systematic difference between the sensitivities for the test size 5.3 min and for 45.6 min. As the stimulus size decreases, the sensitivity decreases in both shorter and longer wavelength ranges. These results are similar to the previous findings^{(9), (10)}. From Fig. 7, no systematic difference between the observers JW and YE can be seen. These features do not depend also on the level of the retinal illuminance ranging from 55 Td to 798 Td.

4.2 Discussion

In the previous investigations, the achromatic channel has been represented by a linear sum of the spectral sensitivities of M and L cones^{(9), (10)}. In Fig. 7, it is shown that the relative sensitivity of the achromatic perception depends on the stimulus size. The results can not be explained by the single achromatic channel model that consists of a linear sum of the spectral sensitivities of M and L cones. Similar results have been found by earlier studies^{(19), (20)}.

In Fig. 7, no systematic difference can be observed among the data at 55, 210 and 798 Td background levels. In the previous investigations^{(21), (22)}, it has been said that according to decrease in the level of retinal illuminance, there exists a changes in the sensitive wavelength of the eye from red to blue. This effect, called the Purkinje effect, is associated with a transition from the cone vision to the rod vision. The Purkinje effect is not observed in the present results, while it is observed in the investigations by Thomson⁽²¹⁾ and by Redford et al.⁽²²⁾. As the reasons why the Purkinje effect is not observed in the present experiments, the following two items can be mentioned: The first one is the difference of the methods. The Purkinje effect is observed in the results that measured by the heterochromatic achromatic matching method^{(21), (22)}. However we have measured the threshold of the achromatic perception. Hence, the Purkinje effect may not be observed in the achromatic perception. The second one is the difference in the level of the retinal illuminance. The Purkinje

effect is obtained at a low illumination level, and indicates that the rod intrusion becomes more prominent. In the present experiments, the levels of the retinal illuminance (55~798 Td) are higher than those of the experiments by Thomson (0.015~29 Td)⁽²¹⁾ and the Redford et al. (7~500 Td)⁽²²⁾.

5. Model Analysis

The results of the psychological experiments show that the spatial characteristic has strong dependency on the wavelength. It is difficult to explain this phenomenon by a conventional single achromatic channel model. In order to explain the experimental results, we propose an achromatic channel model of five stages and three sub-systems having different spatial and spectral characteristics.

5.1 Model Structure

Fig. 8 shows a schematic diagram of the achromatic channel model proposed in this paper. A neural signal from each cone is fed to an ADaptive mechanism (AD). Attenuated receptor signals from M and L cones are then fed separately to A_1 , A_2 and A_3 mechanism depending on the wavelength. The responses of S_1 , S_2 and S_3 mechanism depend on the spatial size of the test

Fig. 8 Schematic diagram of the achromatic channel model

 Fig. 9 Spectral sensitivities of M and L cones

stimulus. Finally, the achromatic perception occurs based on the aggregated signal $[(AS_1)^2 + (AS_2)^2 + (AS_3)^2]^{1/2}$.

(1) Receptive Stage

The receptor functions S , M and L in the model are derived by Smith and Pokorny¹⁸⁾. The spectral sensitivities of M and L are shown in Fig. 9.

(2) Adaptive Stage

The adaptive mechanism has a property that the receptor activity is reduced by an increasing factor as the receptor response increases. The adaptation equation suggested by Naka et al.²³⁾ is used:

$$L' = L \frac{L}{L + \sigma} \quad (3)$$

$$M' = M \frac{M}{M + \sigma} \quad (4)$$

where L and M are the initial responses of the receptors, L' and M' are their response after adaptation at this stage, and $\sigma (= 0.06)$ is a positive constant.

(3) Wavelength Stage

The equations for the mechanism of the wavelength stage are given in terms of the adapted (M' or L') receptor signals.

$$A_1 = -C_1 L' + C_2 M' \quad (5)$$

$$A_2 = C_3 L' + C_4 M' \quad (6)$$

$$A_3 = C_5 L' - C_6 M' \quad (7)$$

where $C_1 \sim C_6$ are positive constants. In this model, we assume that the achromatic channel has no input from S receptors. Guth et al.²⁾ and Smith-Pokorny²⁴⁾ have proposed such structures considering that the response of the S cone is slower than the L and M cones. Our experimental

† In 3.2, the effect of spatial summation is explained by eqs. (1) and (2) based on the Blackwell's model. In our model, the effect of the spatial summation is represented simply by a table for g_1 , g_2 and g_3 .

 Fig. 10 The spectral sensitivity characteristics of the wavelength mechanisms A_1 , A_2 and A_3 have their peaks at short-, middle- and long-wavelength ranges, respectively

results are explained well by the model excluding S cone. The spectral sensitivity characteristics of the wavelength mechanism A_1 , A_2 and A_3 have their peaks at short-, middle- and long-wavelength ranges, respectively (see Fig. 10).

(4) Spatial Stage

The mechanisms S_1 , S_2 and S_3 are the gains depending on spatial size of the test stimulus T_s , and they are represented by the followings:

$$S_1 = g_1(T_s) \quad (8)$$

$$S_2 = g_2(T_s) \quad (9)$$

$$S_3 = g_3(T_s) \quad (10)$$

The values of the functions g_1 , g_2 , g_3 are determined based on the experimental results, and they are given in Table 2† S_1 at 5.3 min is normalized to 1.0.

(5) Perceptive Stage

In the final stage, the achromatic perception is calculated by

$$\sqrt{(A_1 S_1)^2 + (A_2 S_2)^2 + (A_3 S_3)^2}. \quad (11)$$

Eq. (11) means that the achromatic channel is not considered as a single one, but is composed of three subsystems, those have different spatial and spectral characteristics.

5.2 Results and Discussion

The parameters appeared in eqs. (3)~(11) are determined so that the difference between the experimental results and the model prediction attains minimum in the least mean-square sense. As results, eqs. (5)~(7) are shown by the followings:

$$A_1 = -0.27 L' + 0.90 M' \quad (12)$$

$$A_2 = 0.99 L' + 0.21 M' \quad (13)$$

$$A_3 = 0.87 L' - 0.64 M' \quad (14)$$

In the recent studies, a model that the chromatic information participate in the achromatic perception has been proposed³⁾. But the authors have proposed a model that the chromatic¹⁷⁾ and the achromatic information are processed by the independent parallel structure based on the experimental data obtained by the authors.

The wavelength mechanisms A_1 , A_2 and A_3 are shown in Fig. 10. A_2 is a usual single achromatic channel, A_1 and A_3 are qualitatively similar to the yellow-blue and red-green channels, respectively. But as shown in Fig. 10, the curves of A_1 and A_3 have small negative parts and hence we can consider A_1 and A_3 as the subsystems of the achromatic channel.

The values of S_1 , S_2 and S_3 are shown in Table 2. From this table, it can be seen that the spatial mechanism S_1 , S_2 and S_3 have different dependencies on the test size. When the test size is changed from small to large, S_1 and S_3 change remarkably, while S_2 does not.

Predictions by the model are compared with the experimental results (solid curves shown in Fig. 7). The results show that the proposed model of the achromatic perception explains the experimental data in a satisfactory manner. In other words, it suggests that the achromatic channel is composed of three subsystems with different spatial and spectral characteristics

Table 2 Values of the mechanism S_1 , S_2 and S_3

Test size	S_1	S_2	S_3
5.3min	1.0	10.0	3.0
45.6min	90.0	20.0	88.0

6. Conclusion

The purpose of the present paper is to elucidate the parallel structure of the achromatic channel in the human visual system. For this purpose, we have measured the effect of the spatial summation and the relative sensitivity function in the achromatic channel by various psychological experiments, and also investigated them quantitatively based on the proposed model. The principal findings of the study are summarized as follows:

(1) In Experiment 1, the effect of the spatial summation in the achromatic channel is observed. The experimental results show that the spatial characteristics of the achromatic perception depend on the wavelength.

(2) In Experiment 2, the relative sensitivity

functions in the achromatic channel are determined. The experimental results show that the relative sensitivity depend on the test size. This dependence can not be explained by a conventional single achromatic channel model that is a simple linear sum of the spectral sensitivities of M and L cones.

(3) In Experiment 3, the relative sensitivity functions in the achromatic channel have been measured for the two background levels, i.e., at 55 and 798 Td. The results show that the relative spectral sensitivity does not depend on the retinal illuminance level in the range from 55 Td to 798 Td.

(4) It is difficult to explain the above experimental results by a conventional single achromatic channel model. In other words, we must consider the characteristics of the achromatic perception in short-, middle- and long-wavelength ranges separately. This consideration leads to the conclusion that the achromatic information is processed by at least three subsystems.

(5) According to the above conclusion, a five stage model where the achromatic perception is processed by the three subsystems working in parallel is proposed. The model explains the experimental results in a satisfactory manner.

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