Paper

Estimation of Brightness and Lightness in All Adaptation Levels

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ABSTRACT

Brightness and lightness of achromatic surface colors were evaluated under various illuminance conditions in order to make a brightness scale that can be applied for all adaptation levels. A pair of gray scales made up of six gray color chips were presented in a test field and a reference field. Brightness as well as subjective lightness of the six test colors were evaluated using a gray scale in the reference field. Not only haploscopic and also binocular viewing conditions were employed. Furthermore, two comparison techniques—a conventional direct comparison method and a newly developed cascade comparison method—were used in the case of brightness criterion. Experimental results show that the perceived contrast decreased with decreasing Illuminance for the brightness criteria. The contrast compression for a cascade comparison was larger than that for a direct comparison. No contrast compression was obtained for the criterion of subjective lightness.

KEYWORDS : brightness, lightness, adaptation level, mesopic vision

1. Introduction

Human beings can visually perceive objects by adapting to an extremely wide range of illuminance. This adjusting function is attributable to the actions of two kinds of photo receptors in the retina, which are the rods and the cones. The range of illuminance for humans is classified into ranges of adaptation levels: photopic vision for illuminance levels above 10 lux, mesopic vision for levels below 10 lux and above 0.01 lux, and scotopic vision for below 0.01 lux [1]. The cone function mainly in the photopic vision range and the rod in the scotopic vision range. In mesopic vision, which is in the transition process from photopic vision to the scotopic vision, both the cone and the rod function. This results in a complicated visual perception mechanism in which changes in illuminance not only cause changes in spectral luminous efficiency of brightness [2] but also changes in the perception of color [3].

Nowadays, the simulation of images by computer is widely used. How the traffic signs and color of clothes of children are seen in darkness is important for the evaluation of a safe visual environment. Also, it would be useful for selecting colors to know how the colors of buildings and cars are seen in the surrounding illuminance level. When the appearance of objects under low illuminance is simulated, the presented image is generally demonstrated in the photopic level. Also the currently used image input devices, such as the color photo films, the imaging tubes for color televisions and the CCD camera, have been designed so that the human color perception in the photopic vision be represented. Therefore, it has become necessary to precisely evaluate the brightness perception of objects in both the mesopic and scotopic levels in the photopic level in order to properly demonstrate the recreated images in the photopic level.

The haploscopic viewing method has been often used as a tool to estimate the brightness perception of the mesopic and scotopic levels in the photopic level. This method is implemented under the assumption that the right and left eyes separately can be adapted to different adaptation levels[4], and it is suitable for evaluating the brightness of the object color under low illuminance in the condition of direct high illuminance. Direct estimation of brightness on high and low illuminance by haploscopic viewing condition shall be called the "direct comparison method" in this study. However, when the difference in illuminance between the right and left eyes becomes large, the estimation of brightness by the direct comparison method becomes difficult in practice. Thus, a method called the "cascade comparison method" is proposed in this study, in which the difference in illuminance between the right and left eyes is small so that the subjects can estimate the brightness more easily and the estimation of brightness of objects is made step-wise under illuminance conditions closely connecting from low illuminance to high illuminance.

The purpose of this study is to evaluate brightness perception in the mesopic and scotopic levels in the brightness scale in the photopic level by means of both the direct comparison method and the cascade comparison method. On the other hand, it is believed that the perception of brightness is affected by the surrounding environment[5]. Hence, a plurality of color chips with different lightness were prepared and the estimation of brightness perception was implemented with various combinations in order to check how brightness perception varies in relation to the combination of color chips evaluated simultaneously. Also, the perception of lightness was checked in parallel with the brightness perception. In this study, "brightness perception" indicates a feeling if the light emitted from a certain area is seen as plentiful or meager, and "lightness perception" indicates the brightness of a surface judged in comparison with white with high reflectance that is similarly lighted. The subjects in this experiment were instructed in these definitions so that they proceeded to the experiment with this understanding.

2. Measurement of Brightness Perception

2.1 Viewing Methods

Two viewing methods, a haploscopic viewing method and a binocular viewing method, were applied to the experiment. Diagrams of the viewing methods are shown in Fig. 1.

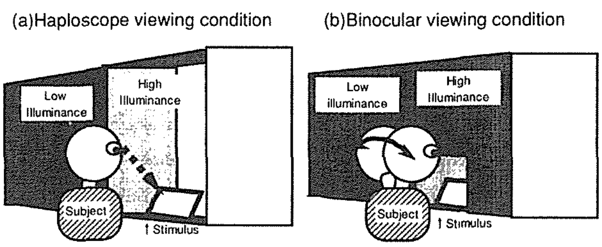

Fig. 1 Viewing conditions. (a) Haploscopic color matching, (b) binocular color matching.

2.1.1 Haploscopic Viewing Method

The haploscopic viewing method is the practice of evaluating the brightness and object color while the right and left eyes are in different adaptation conditions. Since the two different viewing conditions can be set independently, it allows the direct comparative evaluation of the brightness of an object under low illuminance and under high illuminance. Therefore, this is very effective for cases such as the evaluation of brightness perception in the mesopic and scotopic vision ranges alongside of the brightness scale of the photopic level, which was the aim in this study.

2.1.2 Binocular Viewing Method

It commonly happens in our daily life that spaces of largely different lighting conditions are viewed simultaneously with the same adaptation conditions such as the case of viewing something lighted by a spotlight on a dark stage as well the case of viewing an exterior night scene from inside a bright room. The binocular viewing method is the procedure intended to allow brightness evaluation in the condition which is closer to regular perception than the haploscopic viewing condition, which implements the tests after the adaptation of the right and left eyes to different lighting conditions. In this method, the right and left eyes are put in the same adapted condition and the subjects observe and evaluate the brightness of an object under low illuminance and the same object under high illuminance, one by one.

2.2 Experimental Apparatus

For the experimental apparatus, the same observation booth was used for both the haploscopic viewing method and the binocular viewing method. This booth was divided into two sections by a wall, and the inside of each of the two segregated boxes was covered by paper of N5 equivalence. In this study, the right box was set as the standard visual field, which was set at the illuminance of the evaluation standard, and the left box was set as the test visual field, which was set at the illuminance subject to evaluation. The separating wall was covered by black velvet cloth with very low reflectance so that the effect on the other eye could be minimized in the case of observation of the stimulus in each visual field by a single eye. In each box, fifteen fluorescent lamps of approximately D_{65} (Toshiba FL20S · D-EDL-D65) were installed so that the illuminance of standard visual field and test field could be changed independently. There was a device to put black cloth filters below the fluorescent lamps, and the illuminance was varied by adjusting the number of lighted fluorescent lamps and the number of black cloth filters. Following are the differences in the apparatuses for the different viewing methods.

For the haploscopic viewing method, a chin rest with a curtain and another curtain covering each box were set in front of the separating wall so that the light in each visual field does not leak to the other field. The subjects inserted their faces in the opening between the chin rest and the curtain and performed the experiment with the forehead touched the separating wall.

For the binocular viewing method, the front side of the booth that was used for the haploscopic viewing method was covered by paper of N5 equivalence, in which windows were set so that only the stimuli and their vicinity could be seen. Then, the subjects were instructed to view the standard visual field and the test visual field alternately for several seconds each with both eyes so that adaptation did not become biased to the illuminance of only one of the two stimuli.

2.3 Stimulus

For the stimulus, six gray color chips (N1, N2.5, N4.5, N6.5, N8, N9.5) were used, which were placed in a row. For the color chips, the standardized color chips based on the Munsell color system were adopted. The size of each color chip was 10° x 7.6°. The design of the stimulus is shown in Fig. 2. Two sets of the same stimulus were prepared and each one was set in each of the two visual fields for the experimental apparatus.

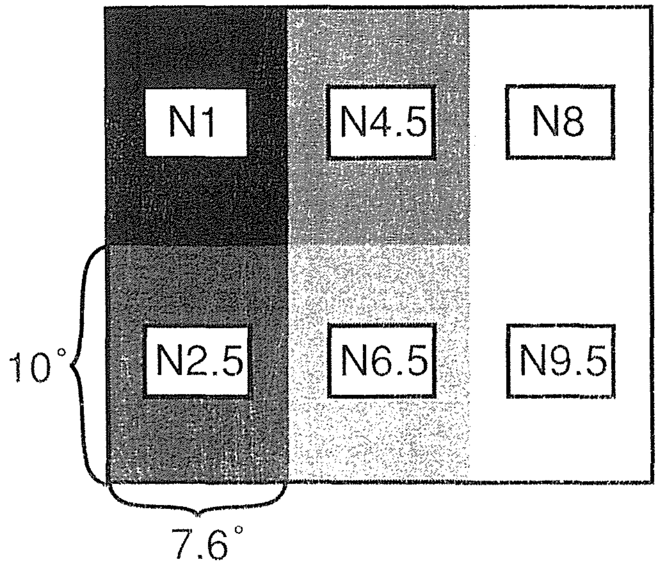

Fig. 2 Test stimulus consists of six gray color chips.

2.4 Evaluation Method for Brightness

Direct comparison method and cascade comparison method were applied for evaluation of brightness.

2.4.1 Direct Comparison Method

The brightness of object color under low illuminance conditions was evaluated by reference to a direct high illuminance condition despite the difference in illuminance. A feature of the direct comparison method is that it allows the direct evaluation of color appearance under largely different illuminances.

2.4.2 Cascade Comparison Method

The difference in illuminance for the right and left eyes was reduced and the perception of the objects' brightness was evaluated step by step from low illuminance to high illuminance, so that the subjects could easily evaluate the brightness.

2.5 Experimental Conditions

In this study, the reference illuminance was set in the standard visual field side and the illuminance for the estimation of the object was set in the test visual field side.

In the direct comparison method, the illuminance of the reference visual field was set at 1000 lux and the illuminance of the test visual field was set at six levels, or 1000, 100, 10, 1, 0.1, and 0.01 lux. The subjects compared and evaluated the brightness of the stimulus in the test field under each illuminance condition versus the brightness of the stimulus in the reference field.

In the cascade comparison method, the illuminance of the reference field was set at five levels, or 1000, 100, 10, 1, and 0.1 lux, and the test field was set at six levels, or 1000, 100, 10, 1, 0.1, and 0.01 lux. In the cascade comparison method, the illuminance of the reference field was always set at one rank higher level than the illuminance of the test field. For example, when the illuminance of test field was 0.1 lux, the illuminance of the reference field was 1 lux, and when the illuminance of the test field was 10 lux, the illuminance of the reference field was 100 lux. Subjects compared and evaluated the brightness of the test field versus the brightness of the stimulus in the reference field step by step, starting with the low illuminance condition in the test field. A scheme of the experimental conditions is shown in Fig. 3.

In all experiments, 15 minutes of adaptation in darkness and 5 minutes of adaptation in the adapting illuminance condition were made before starting the experiment. The number of subjects was four. All of them had normal color perception.

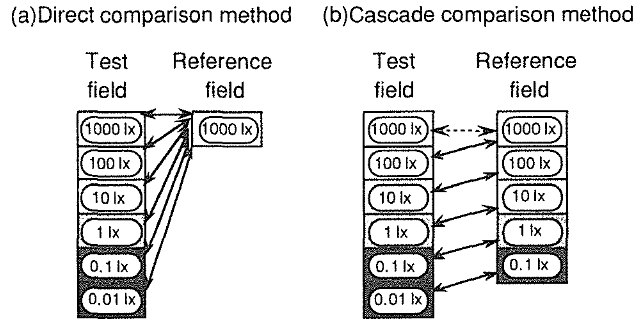

Fig. 3 Evaluation methods. (a) Direct comparison method, (b) cascade comparison method.

2.6 Subjective Evaluation of Brightness

In order to evaluate the brightness of the test field based upon the brightness perception of the reference field, it was necessary to assign numerical values to the brightness perception of the color chips in the reference field in a preparatory stage in this study. These assigned numerical values were called the "subjective evaluation of brightness."

2.6.1 Stimulus

The same stimuli as previously described were applied. The subjective evaluation of brightness was implemented on all illuminance conditions of the evaluation standard (0.1 lux, 1 lux, 10 lux, 100 lux and 1000 lux). Under each illuminance condition, a brightness 1 was assigned to the color chip N1 and a brightness of 10 was assigned to N9.5. Using the levels for these two color chips as the basis, numerical values for brightness were assigned for each color chip N2.5, N4.5, N6.5 and N8.

2.6.2 Results

Examples of the results of the subjective evaluation of brightness are shown in Fig. 4. The horizontal axis shows the value of lightness of the color chips used as stimuli, and the vertical axis shows the subjective evaluation of brightness. Each plot shows illuminance. ● shows the results at 1000 lux, ■ at 100 lux, ▲at 10 lux, ○ at 1 lux, and □ at 0.1 lux. Since the level of lightness of the color chips was assigned in even intervals versus psychological brightness, the subjective evaluation of subjects was assumed to change linearly (on a straight line of 45°) versus the levels of lightness of the color chips.

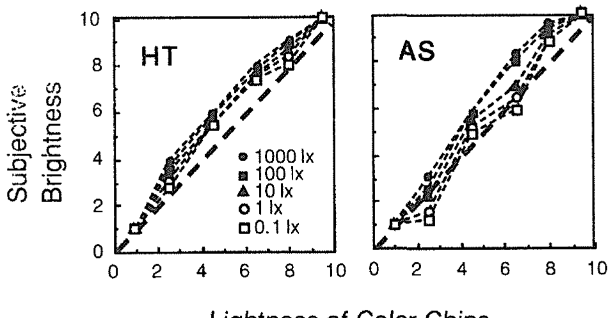

Fig. 4 Experimental results of the subjective brightness evaluation by subjects HT and AS.

Although the results of the subjective evaluation of brightness by all the subjects were on a straight line of 45° connecting brightness 1 and 10, a slight decreases in the evaluation level of brightness associated with a decrease in illuminance was observed. Based on these results, the evaluation of brightness by direct comparison as well as by cascade comparison were implemented. Only the results of subjective evaluation of brightness for 1000 lux was applied for direct comparison, while all of the results were used for cascade comparison.

2.7 Evaluation of Brightness

The process of evaluating brightness is explained as follows. The brightness of each color chip in the reference field had been already assessed by the subjective evaluation of brightness. The subjects performed the evaluation of brightness of each color chip in the test field by reporting its allocated position in the color chips in the reference field by numerical value. For example, let us assume that the brightness of a color chip N6.5 in the test field was perceived to be equivalent to a brightness in between N4.5 and N6.5 in the reference field. In such a case, the subject indicates the brightness of the color chip that is the object of evaluation as "○ tenths of brightness between N4.5 and N6.5". (A larger value of ○ indicates that the brightness is closer to N6.5.) The assigned level of brightness evaluation from each subject was converted to a numerical value using the results obtained through the subjective evaluation of brightness. By the way, when the brightness of a color chip in the test field was perceived to exceed the range of brightness of the color chips in the reference field, it was allowed to be assigned a value outside the range.

2.8 Correction of Cascade Comparison

It is the purpose of this study to evaluate brightness perception in the mesopic and scotopic levels by the brightness scale of the photopic level. In the direct comparison method, the obtained results were those evaluated by the brightness scale of the photopic level since the reference field was constant at 1000 lux. In the cascade comparison method, however, it was necessary to normalize the evaluation standard to the brightness scale of 1000 lux, which was the same as the case of the direct comparison, since the illuminance of the evaluation standard is not constant. In order to normalize the brightness scale, the results in the cascade comparison method were corrected. The steps of correction are explained in Fig. 5, which is an example of the case with 10 lux of the test field and 100 lux in the reference field.

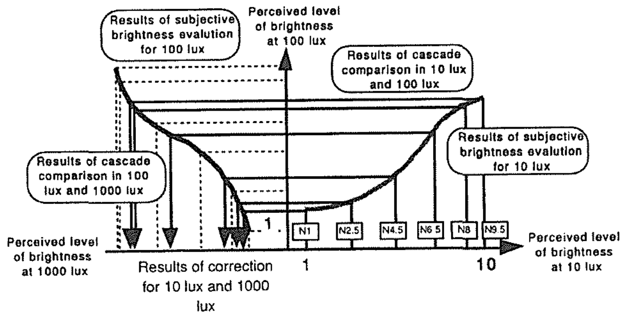

Fig. 5 Explanatory diagram for the cascade comparison method.

Step 1 : The results of each color chip under subjective brightness evaluation in case of 10 lux are shown on the horizontal axis. The results of each color chip under cascade comparison for 100 lux of reference field and 10 lux in the test field are shown in vertical axis. The relationship between these two results are approximated by a third dimension equation.

Step 2 : Similarly, the results of the subjective brightness evaluation in case of 100 lux are shown in vertical axis and the results of cascade comparison in case of 1000 lux in the reference field and 100 lux in the test fields are shown in horizontal axis, and then a third dimension equation is obtained.

Step 3 : The numerical value of each color chip as assumed to be perceived incrementally, starting from the results of 10 lux of subjective brightness evaluation so that the brightness evaluation of each color chip at 10 lux can be expressed by the brightness scale in 1000 lux which was aimed at.

Following the same steps, the results in cases of 0.1-0.01 lux, 1-0.1 lux, and 10-1 lux in cascade comparison were corrected so that normalization of the brightness scale for cascade comparison in the photopic level could be realized.

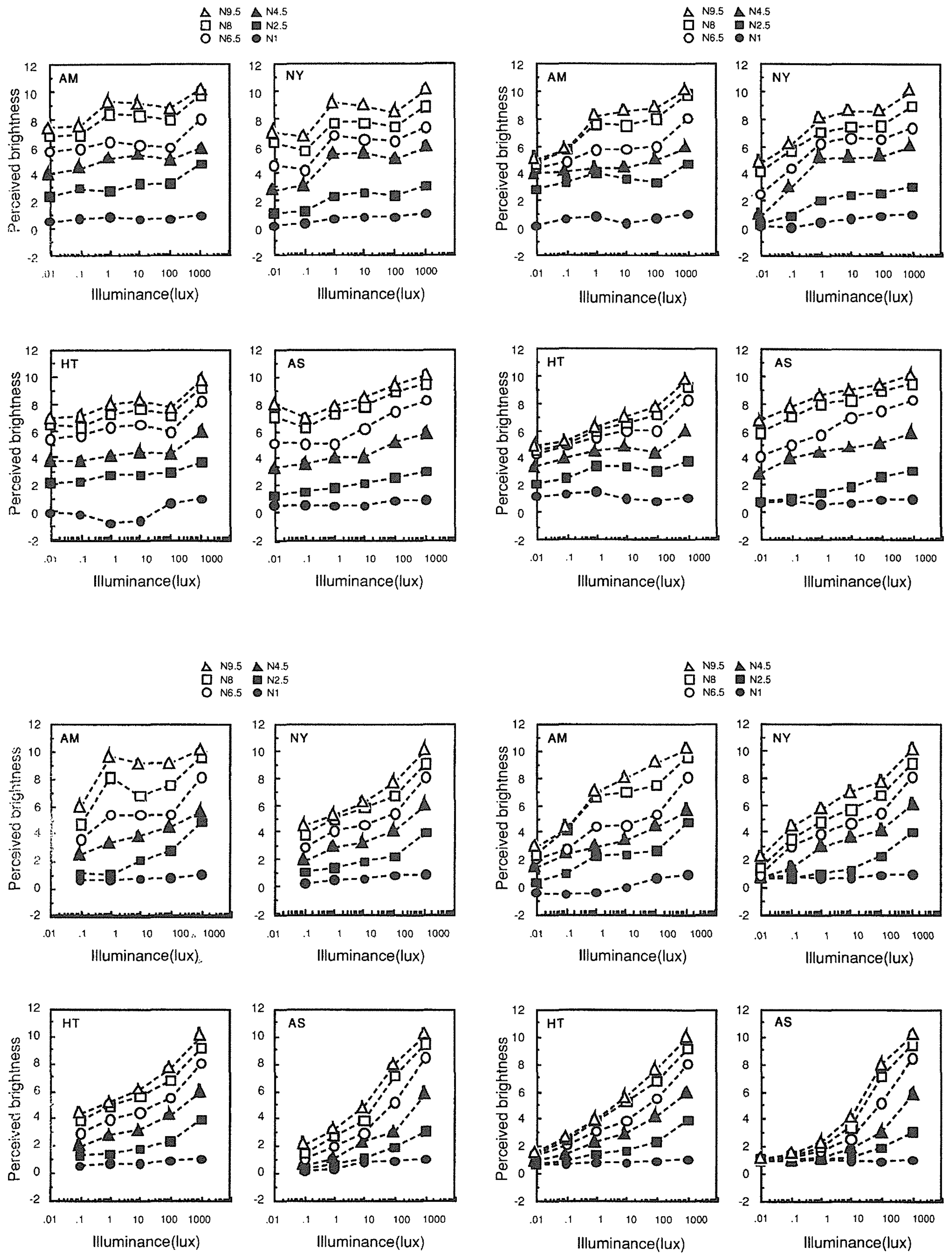

Fig. 6 Experimental results for brightness perception. (a) Haploscopic color matching with direct comparison method, (b) haploscopic color matching with cascade comparison method, (c) binocular color matching with direct comparison method, and (d) binocular color matching with cascade comparison method.

2.9 Results

The results are shown in Fig. 6-1 through Fig. 6-4. The horizontal axis shows the illuminance of the object of evaluation and the vertical axis shows the perceived brightness. Each plot indicates a color chip. △ indicates the results for N9.5, □ for N8, ○ for N6.5, ▲for N4.5, ■ for N2.5, and ● for N1.

In the haploscopic viewing method, both the direct comparison method (Fig. 6-1) and the cascade comparison method (Fig. 6-2) showed the Stevens Effect in which contrasts are compressed in parallel with a decrease in illuminance. However, this effect was small in the direct comparison method. A significantly large Stevens Effect was observed with the cascade comparison method. Although Stevens described black becoming more black when illuminance level is increased [6], the Stevens Effect with black was not strongly revealed in this experiment.

In the binocular viewing condition, a large compression in brightness contrast was observed in both the direct comparison method (Fig. 6-3) and the cascade comparison method (Fig. 6-4).

2.10 γ-Characteristics, Degree of Compression, and Central Points

In order to check the overall tendency of changes in perceived brightness associated with decrease in illuminance, γ-characteristics, the degree of compression and the central points for each experimental result were obtained. Firstly, the logarithm of the reflection luminance of the color chips is put in the horizontal axis for all the results. The vertical axis of the graph indicates the perception of brightness. When the data was re-plotted, a graph as shown in Fig. 7 was obtained. Similar results have been obtained by an experiment of electrical physiology, in which apes were used [7]. Each symbol indicates illuminance, and the six points of each illuminance correspond to the color chips. When the perceived brightness of each color chip is connected to its corresponding reflection luminance, it makes an almost straight line. Hence, the results of brightness perception in each illuminance were approximated by a one-dimensional equation, and its slope is defined as the γ-characteristic. When the level of γ-characteristic is greater, it indicates that the contrast of brightness perception is larger.

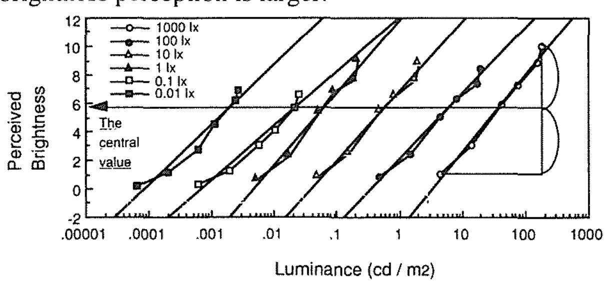

Fig. 7 γ-characteristics and the central value.

The ratio of the level of γ-characteristic in each illuminance to the level of γ-characteristic at 1000 lux was defined as the degree of compression. If the contrast of the object is smaller than that of the standard, it takes value below 1, and when it exceeds 1, it means that contrast of the object is larger than that of the standard. Also, as an index to show the deviation of the range of brightness perception, the averages of the maximum and minimum levels of brightness perception were calculated, which were called the central points. Therefore, the central points are averages of the brightness perception of N9.5 and that of N1. It is known that if the central points are high, the overall brightness perception has been shifted toward the brighter (white) direction and, if it is low, toward the darker (black) direction. The degree of compression and the brightness perception for the four subjects are shown in Table 1-1 and Table 1-2.

Table 1-1 The degree of compression for the brightness perception.

AM

Illuminance (lux)	Haploscope -Direct	Haploscope -Cascade	Binocular -Direct	Binocular -Cascade
1000	1.00	1.00	1.00	1.00
100	0.87	0.87	0.89	0.89
10	0.91	0.85	0.88	0.84
1	0.94	0.77	1.03	0.82
0.1	0.75	0.56	0.59	0.55
0.01	0.77	0.50		0.37

NY

Illuminance (lux)	Haploscope -Direct	Haploscope -Cascade	Binocular -Direct	Binocular -Cascade
1000	1.00	1.00	1.00	1.00
100	0.84	0.84	0.76	0.76
10	0.89	0.87	0.65	0.88
1	0.94	0.85	0.56	0.58
0.1	0.70	0.71	0.46	0.42
0.01	0.78	0.53		0.12

HT

Illuminance (lux)	Haploscope -Direct	Haploscope -Cascade	Binocular -Direct	Binocular -Cascade
1000	1.00	1.00	1.00	1.00
100	0.78	0.78	0.75	0.75
10	0.96	0.66	0.61	0.55
1	0.95	0.53	0.54	0.38
0.1	0.79	0.46	0.43	0.23
0.01	0.79	0.43		0.10

AS

Illuminance (lux)	Haploscope -Direct	Haploscope -Cascade	Binocular -Direct	Binocular -Cascade
1000	1.00	1.00	1.00	1.00
100	0.94	0.94	0.72	0.72
10	0.86	0.92	0.35	0.29
1	0.79	0.88	0.23	0.14
0.1	0.69	0.79	0.15	0.03
0.01	0.81	0.66		0.01

Regarding the degree of compression, it was recognized that the compression of the contrast of brightness perception was small in haploscopic viewing situation with the direct comparison method on all subjects. In the haploscopic viewing situation with the cascade comparison method, the degree of contrast compression was smaller compared to the direct comparison method with almost all the subjects.

It was known that, in the binocular viewing situation, the contrast was perceived with significant compression when the illuminance was decreased compared to the haploscopic viewing situation. Although the degree of contrast compression was large, especially in binocular viewing situation with the cascade comparison method in all subjects, individual differences in the degree of compression were observed.

Table 1-2 The central points for the brightness perception.

AM

Illuminance (lux)	Haploscope -Direct	Haploscope -Cascade	Binocular -Direct	Binocular -Cascade
1000	5.52	5.52	5.54	5.54
100	4.71	4.71	4.92	4.92
10	4.92	4.40	4.90	4.06
1	5.07	4.47	5.13	3.33
0.1	4.15	3.19	3.26	1.96
0.01	3.95	2.60		1.30

NY

Illuminance (lux)	Haploscope -Direct	Haploscope -Cascade	Binocular -Direct	Binocular -Cascade
1000	5.50	5.50	5.52	5.52
100	4.63	4.66	4.30	4.30
10	4.85	4.58	3.46	3.87
1	4.88	4.18	2.94	3.26
0.1	3.49	3.08	2.45	2.63
0.01	3.55	2.44		1.52

HT

Illuminance (lux)	Haploscope -Direct	Haploscope -Cascade	Binocular -Direct	Binocular -Cascade
1000	5.41	5.41	5.50	5.50
100	4.24	4.24	4.27	4.27
10	3.88	4.00	3.36	3.17
1	3.62	3.86	2.90	2.36
0.1	3.53	3.25	2.43	1.63
0.01	3.49	3.01		1.09

AS

Illuminance (lux)	Haploscope -Direct	Haploscope -Cascade	Binocular -Direct	Binocular -Cascade
1000	5.55	5.55	5.53	5.53
100	5.13	5.13	4.46	4.46
10	4.47	4.85	2.35	2.12
1	4.20	4.62	1.41	1.47
0.1	3.77	4.25	0.83	1.07
0.01	4.29	3.73		0.83

Regarding the central points, the central points at 0.01 lux were in the range from 3.5 to 4.0 of brightness at 1000 lux in the haploscopic viewing condition with the direct comparison method, and in the range from 2.5 to 3.0 in the cascade comparison method in almost all subjects. Subject AS showed higher levels than these ranges. His central point in the direct comparison method was 4.29, while his central point in the cascade comparison method (3.73) was in the equivalent range of the direct comparison method for the other subjects. From this fact, it was suggested that in the haploscopic viewing condition, subject AS had brightness perception in the cascade comparison similar to that in the direct comparison.

On the other hand, in the binocular viewing situation, the central points of 0.1 lux under the direct comparison method showed individual differences and it was in the range from 0.8 to 3.3. Furthermore, the central values at 0.1 lux under the cascade comparison method were concentrated in the vicinity of 1. Considering this fact along with the results of the degree of compression, it is known that, when there are two illuminances with and extremely large difference in the same space, objects on the side of low illuminance are perceived as almost black despite the objects' reflectance.

3. Subjective Evaluation of Lightness

It was known that, when illuminance is decreased, brightness is perceived with compressed contrast. On the other hand, in daily life we perceive the attribute of reflectance possessed by the color chips, such as whiteness and blackness, as brightness pertinent to the objects regardless of the illuminance. This attribute of reflectance held by the color chips was defined as "subjective lightness" in this study, and the subjective lightness was measured under the same illuminance conditions as those in the direct comparison method for brightness evaluation.

3.1 Observation Method, Experimental Apparatus, and Stimulus

The haploscopic viewing method and the binocular viewing method were adopted for the observation methods. The same experimental apparatus and stimulus as used for measuring brightness perception were used.

3.2 Evaluation of Subjective Lightness

Subjective lightness was measured only by the direct comparison method in this study. Subjects evaluated the subjective lightness of each color chip or evaluation object under each illuminance (six steps of 1000, 100, 10, 1, 0.1, and 0.01 lux) by reporting numerical values approximating the assigned lightness of color chips under the evaluation standard illuminance of 1000 lux. The details of the steps are the same as those in the brightness evaluation.

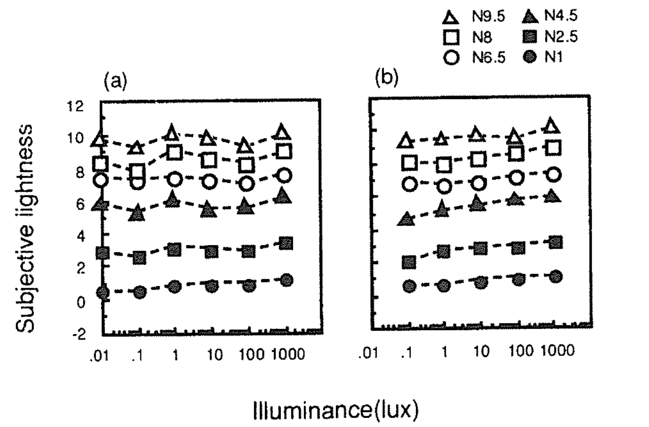

Fig. 8 Experimental results of the subjective lightness evaluation by subject NY. (a) Haploscopic color matching with direct comparison method, (b) binocular color matching with direct comparison method.

3.3 Experimental Results

As an example, the results of subject NY are shown in Fig. 8. The horizontal axis shows the illuminance of the objects of evaluation, and the vertical axis shows the subjective lightness perceived by the subject. Each plot indicates a color chip. The subjective lightness was almost constant for all illuminance level with the other three subjects. The same tendency was observed on the results with both the haploscopic viewing method and the binocular viewing method.

3.4 Degree of Compression and Central Points

The degree of compression and the central points on the results of the subjective lightness perception of the four subjects are shown in Table 2.

Table 2 The degree of compression and the central points for the subjective lightness.

AM

Illuminance (lux)	Degree of Compression		Central points	
	Haploscope -Direct	Binocular -Direct	Haploscope -Direct	Binocular -Direct
1000	1.00	1.00	5.60	5.53
100	1.03	1.01	5.48	5.52
10	1.04	1.04	5.41	5.57
1	1.09	1.08	5.48	5.42
0.1	1.04	1.00	5.34	5.24
0.01	1.02		5.32	

NY

Illuminance (lux)	Degree of Compression		Central points	
	Haploscope -Direct	Binocular -Direct	Haploscope -Direct	Binocular -Direct
1000	1.00	1.00	5.56	5.63
100	0.94	0.96	5.04	5.22
10	0.98	0.97	5.31	5.24
1	1.04	0.96	5.42	5.02
0.1	0.97	1.01	4.77	4.92
0.01	1.03		5.03	

HT

Illuminance (lux)	Degree of Compression		Central points	
	Haploscope -Direct	Binocular -Direct	Haploscope -Direct	Binocular -Direct
1000	1.00	1.00	5.41	5.50
100	0.75	0.87	4.18	4.77
10	1.01	0.87	4.13	4.68
1	1.01	0.90	4.03	4.67
0.1	0.89	0.83	3.80	4.45
0.01	0.97		4.35	

AS

Illuminance (lux)	Degree of Compression		Central points	
	Haploscope -Direct	Binocular -Direct	Haploscope -Direct	Binocular -Direct
1000	1.00	1.00	5.34	5.54
100	0.98	0.96	5.21	5.38
10	0.99	0.99	5.07	5.45
1	0.98	0.96	5.03	5.27
0.1	0.92	0.76	4.95	4.66
0.01	0.90		4.89	

The degree of compression of subjective lightness was in the range from 0.9 to 1.1 in the scope of all illuminance for all the subjects. Thus, it was confirmed that the contrast of subjective lightness was almost constant despite a decrease in illuminance.

Regarding the central points, a tendency was observed that the central points decreased slightly in parallel with a decrease in illuminance depending on the subjects. However, since the reduction was very small compared to the reduction that had been obtained in the results of brightness perception, subjective lightness can be said to have significantly high constancy in regard to illuminance compared to brightness perception.

From this experiment, it was clarified that, although brightness perception is changed by a decrease in illuminance, lightness is evaluated precisely regardless of the illuminance level.

4. Effect of Surrounding Environment on Brightness Perception

It was clarified by the results of the subjective lightness perception experiments that the luminance of color chips is precisely evaluated irrespective of the illuminance level. However, there is a possibility that the following two factors largely affected the result; i.e. (1) subjects recognized the test color chips since the same stimulus was used in both the test field and the reference field, and (2) the stimulus included both black and white. In order to further check this point, several kinds of stimuli in the test field were prepared in order to study the changes in brightness perception and subjective lightness perception by changes in contrast of overall color chips.

4.1 Observation Method

The binocular viewing method in which the difference between the brightness perception and the subjective lightness perception is large was applied.

4.2 Stimulus

Four kinds of stimuli were used for the test field stimuli. In each of them four out of the six color chips (N1, N2.5, N4.5, N6.5, N8 and N9.5) were placed in a row. The size of each color chip was 10°x7.6°.

Stimulus 1 : Composed of N1, N4.5, N6.5 and N9.5
(White and black included)

Stimulus 2 : Composed of N4.5, N6.5, N8 and N9.5
(Black excluded)

Stimulus 3 : Composed of N1, N2.5, N4.5 and N6.5
(White excluded)

Stimulus 4 : Composed of N2.5, N4.5, N6.5 and N8
(White and black excluded)

In the reference field, the same stimulus was installed as was used in the previous experiments. The direct comparison method was applied to both the evaluation of brightness and the evaluation of subjective lightness in this study. By the way, the composition of stimulus was not revealed to subjects before the test except to subject HT.

4.3 Experimental Results

4.3.1 Results of Brightness Evaluation

As an example of the results of brightness perception, the results of subject HT are shown in Fig. 9. Cases (a), (b), (c), and (d) are the results with stimuli 1, 2, 3, and 4 respectively. The horizontal axis shows the illuminance of the evaluation objects and the vertical axis shows the evaluation of brightness perceived by the subject. Each plot indicates a color chip. The contrast of brightness perception accompanying a decrease in illuminance was greater with stimuli 1 through 4 when compared to the cases with six pieces of color chips. Especially, the color chips with relatively high illuminance such as N8 and N6.5 were perceived to be brighter compared to the cases with six color chips.

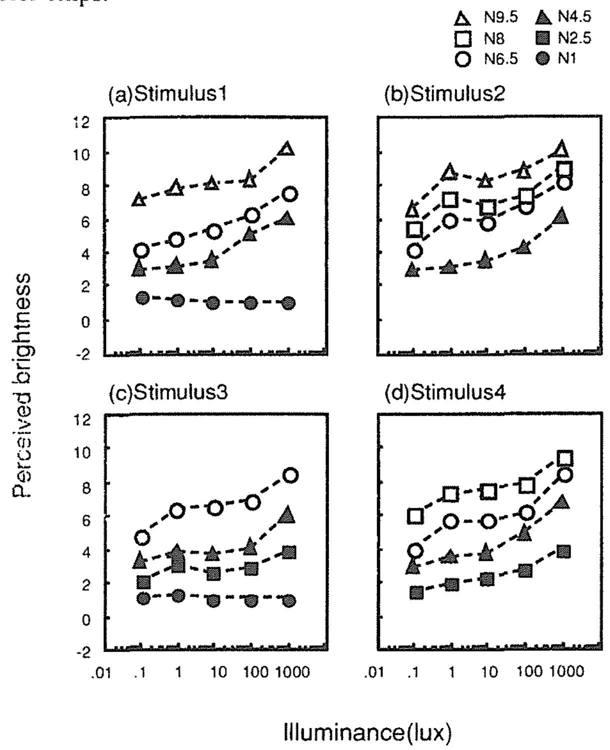

Fig. 9 Experimental results for brightness perception by subject HT. (a) Including white and black, (b) excluding black, (c) excluding white, and (d) excluding both white and black.

The degree of compression of each stimulus versus the results with six color chips are shown in Table 3-1. The central point of each stimulus is shown in Table 3-2. The central point corresponding to each stimulus based on the results of the cases with six color chips is shown in Table 3-3. The results of two subjects are shown here. It was observed that the perceived contrasts were large in all stimuli irrespective of luminance compared to the results of the cases with six color chips on all subjects, including the other two subjects. However, it was observed that the expansion of the degree of compression occurred between the vicinity of 1 and 1.6. Also, it was observed by comparing Table 3-2 and Table 3-3 that the levels of the central points were similar or higher compared to the central points obtained from the results of the cases of six color chips and that this tendency was conspicuous with low illuminance. In short, it can be said that, when the number of brightness (color chips) to be evaluated at the same time is small, overall perception shifts toward the brighter side in parallel with a decrease in illuminance.

Table 3-1 The degree of compression for the brightness perception using each simulus made up of 6 color chips.

TH

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	0.99	0.96	1.05	1.05
100	1.08	1.22	1.18	1.15
10	1.29	1.45	1.40	1.38
1	1.39	2.16	1.39	1.53
0.1	1.42	1.49	1.54	1.76

NY

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	0.94	0.95	0.91	1.13
100	1.07	1.28	1.13	1.16
10	1.24	1.57	1.58	1.40
1	1.23	2.29	1.50	1.71
0.1	1.11	1.34	0.80	2.09

Table 3-2 The central points for the brightness perception using each stimulus made up of 4 color chips.

TH

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	5.51	7.99	4.67	6.65
100	4.60	6.43	3.91	5.18
10	4.47	5.77	3.73	4.83
1	4.43	5.82	3.82	4.55
0.1	4.14	4.65	2.92	3.66

NY

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	5.52	8.01	4.19	6.29
100	4.60	6.03	3.41	4.36
10	4.25	5.74	3.90	4.23
1	3.72	4.29	3.39	4.26
0.1	2.62	2.31	1.41	3.18

Table 3-3 The central points for the brightness perception using each stimulus made up of 6 color chips.

TH

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	5.50	7.96	4.50	6.51
100	4.27	5.92	3.18	4.53
10	3.36	4.57	2.55	3.72
1	2.90	3.94	2.29	3.15
0.1	2.43	3.17	1.70	2.54

NY

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	5.52	8.02	4.52	6.58
100	4.30	5.92	3.19	4.52
10	3.46	4.79	2.65	3.89
1	2.94	4.15	2.38	3.28
0.1	2.45	3.27	1.68	2.59

4.3.2 Results of Subjective Lightness Evaluation

The results of the subjective lightness evaluation are shown in Fig. 10. The horizontal axis shows the illuminance of the evaluation objects and the vertical axis shows the subjective lightness perceived by the subjects. Each plot indicates a color chip. Although all subjects showed constant subjective lightness irrespective of illuminance, the perception of subjective lightness significantly changes with illuminance when the combination of color chips was changed.

In the results for stimulus 2 and 4 (Fig. 10 (b) and (d)) in which color chip N1, the representation of black, was not included, the overall contrast of subjective lightness expanded in the dark direction. This is considered to be attributable to a large decrease in the subjective lightness of the color chips, the physical lightness of which was relatively the lowest among all the color chips composing each stimulus (N4.5 in stimulus 2 and N2.5 in stimulus 4).

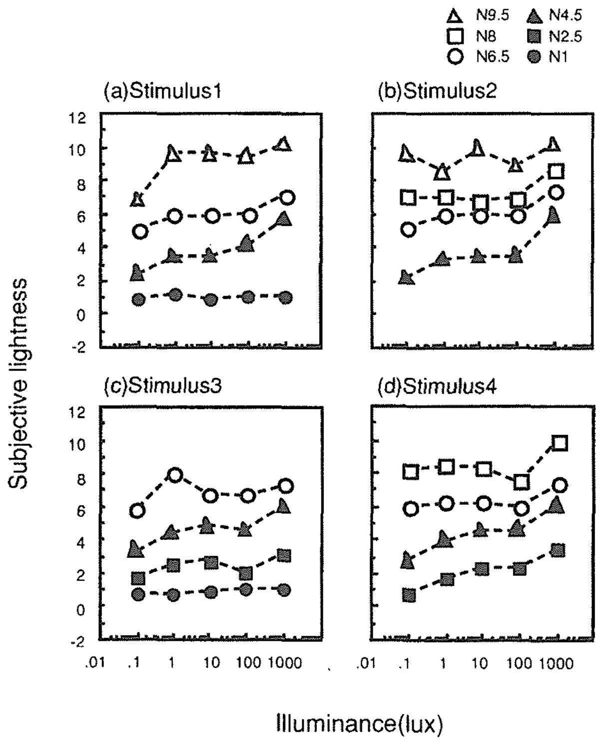

Fig. 10 Experimental results for lightness perception by subject HY. (a) Including white and black, (b) excluding black, (c) excluding white, and (d) excluding both white and black.

Similarly, in the results of stimulus 3 and 4 in which the color chip of N9.5, the representation of white was not included (Fig. 10 (c) and (d)), the overall contrast of subjective lightness expanded toward brightness. This is considered to be attributable to a large increase in subjective lightness of the color chips, the physical lightness of which was relatively the highest among all the color chips composing each stimulus (N6.5 in stimulus 3 and N8 in stimulus 4).

The degree of compression for each stimulus versus the results tested with six color chips is shown in Table 4-1. The central point of each stimulus is shown in Table 4-2. The central point corresponding to each stimulus based on the results of the cases with six color chips is shown in Table 4-3. The results for two subjects are again shown here. Regarding to the degree of compression, contrast remained almost unchanged in all stimuli for all subjects, including the other two subjects, compared to the results in the cases of tests with six color chips. The degree of compression was mostly in the range from approximately 0.8 to 1.3. Especially in case of subject HT, who knew the composition of the stimuli, it concentrated in the vicinity of 1.0.

It was known that the central points for stimulus 2 and 4 were lower compared to the central points obtained from the results of the tests with six color chips for almost all subjects, and that tendency became stronger when the illuminance was lowered. With stimuli 1 and 3, there were no large differences in the central points versus the results of the cases in which stimuli 1 through 4 and six pieces of color chips were used. In the case of subject HT, a tendency was observed that all stimuli had slightly higher central points compared to the central points obtained from the results with six color chips when the illuminance was decreased.

Table 4-1 The degree of compression for the subjective lightness using each stimulus made up of 6 color chips.

TH

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	0.99	0.98	1.01	1.03
100	1.11	0.91	1.21	0.98
10	1.11	0.82	1.36	0.98
1	0.94	0.91	1.24	1.00
0.1	0.94	1.05	1.18	0.97

NY

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	1.00	0.95	1.03	1.10
100	0.93	1.30	0.89	0.91
10	0.95	1.36	0.95	1.12
1	0.90	1.21	1.10	1.27
0.1	0.65	1.51	0.77	1.22

Table 4-2 The central points for the subjective lightness using each stimulus made up of 4 color chips.

TH

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	5.50	7.95	4.50	6.50
100	5.09	7.17	4.20	5.89
10	5.09	6.87	4.23	5.83
1	5.58	7.11	4.20	6.04
0.1	5.10	6.60	4.15	5.78

NY

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	5.52	7.93	4.17	6.67
100	5.16	6.11	3.82	4.88
10	5.20	6.55	3.78	5.28
1	5.36	5.82	4.37	5.05
0.1	3.82	5.82	3.23	4.46

Table 4-3 The central points for the subjective lightness using each stimulus made up of 6 color chips.

TH

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	5.50	7.95	4.49	6.54
100	4.77	6.74	3.53	5.34
10	4.68	6.26	3.19	5.10
1	4.67	6.58	3.27	5.47
0.1	4.45	6.20	3.45	4.88

NY

Illuminance (lux)	Stimulus1	Stimulus2	Stimulus3	Stimulus4
1000	5.63	7.95	4.24	6.05
100	5.22	7.58	4.05	5.71
10	5.24	7.53	3.85	5.56
1	5.02	7.28	3.69	5.30
0.1	4.92	6.95	3.68	5.02

5. Discussion

The brightness perception and the subjective lightness perception accompanying a decrease in illuminance were evaluated in this study by simultaneously displaying a plurality of color chips.

The Stevens Effect, in which contrast is compressed in parallel with a decrease in illuminance, was observed in the results of both the direct comparison method and the cascade comparison method under the haploscopic viewing situation. This tendency was stronger with the cascade comparison method, and there was a possibility that the brightness of stimulus in the side of low illuminance was naturally perceived to be dark, since it was judged as if both the test field and reference field were lighted in the same illuminance due to adjacent adaptation illuminance of these fields. A strong Stevens Effect was observed in the binocular viewing situation, as was observed in the cascade comparison method under the haploscopic viewing situation, irrespective of the method of brightness evaluation. Also it was clarified that the evaluation of the subjective lightness perception of the color chips was constant irrespective of the illuminance level, and the same tendency was observed in the results under both viewing situations.

The above results were obtained on the same color chips composed of six color chips including white and black, which were placed in both the test and reference field. Therefore, an assumption that the following two factors contributed to the obtained results on the subjective lightness perception, as mentioned in the above, could not be denied:

(1) The same stimuli were used in both the test and the reference field.

(2) Stimuli including both black and white was used.

In order to check the effects of these factors, several kinds of stimuli for the test field with a changing combination of lightness were prepared, and the changes in brightness perception and the subjective lightness perception due to changes in contrasts of overall color chips were studied. In the results, the overall lightness perception expanded toward white in parallel with a decrease in illuminance in the stimuli with combinations that excluded white, and similarly, it expanded toward black with the combinations excluding black. That is to say, it did not happen that "the subjective lightness perception is evaluated at a constant level irrespective of illuminance level" in the combination of brightness which does not include white or black. Also, it was known that the subjective lightness perception is evaluated at a constant level irrespective of the illuminance level even in the combinations of brightness that excluded white or black when the composition of the stimulus was known to the subject. In conclusion, it was clarified that the two factors as mentioned above are the conditions for the lightness of objects to be always perceived at a constant level.

In order to clarify the controlling factors for the constancy of brightness, various types of experiments have been arranged in the past. In general, there is the fact that the constancy of brightness in the daily space is higher than that in the experiment in experimental facilities[8]. From the results of this study, it was clarified that the constancy of brightness is realized irrespective of lightness when the brightness of objects is already known. Since the brightness of objects is already known in the daily space, from the results of this study it is considered natural that the constancy of brightness in the daily space is higher compared to the data on subjects who perform the tasks in conditions where the details of the test parameters are unknown to them. However, even if the brightness of objects is unknown, the constancy of brightness is realized when there are objects equivalent to white and black in the visual field. It is considered to be desirable that the simulation of brightness perception under low illuminance is implemented taking these facts into consideration.

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