A Study of Simultaneous Lightness Perception for Stimuli with Multiple Illumination Levels

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Abstract

Color appearance models can provide predictions of the perception for color, including visual phenomena such as chromatic adaptation. Color matching of a print with a monitor is one good example in which color appearance models play a significant role. Recently the performance for more complex and higher dynamic range stimuli has come to be required. This paper focuses on the problem of the simultaneous perception of lightness in a bipartite background. The perceived lightness of a pair of stimuli on the bipartite background was measured at various luminance and contrast levels and positions. The results are analyzed by using existing color appearance models. A concept of the global and local lightness is introduced to evaluate the perceived lightness.

Introduction

Color appearance models (CAM) have been developed through much effort and CIECAM02 was released recently.[1,2] In such a model as CIECAM02, the spatial arrangement of stimulus and background is specifically defined. At the next stage, the goal must be to build image appearance models that provide the prediction of the perception of more spatially complex images. A considerable number of studies have been conducted on the perception of complex images.[3-5] However, it is sometimes difficult to compare data when measured under widely differing viewing conditions, such as luminance level. It might be useful to link the study of perception for spatially complex images with existing color appearance models in the viewpoint of incorporating knowledge about color appearance phenomena, as proposed in the concept of iCAM.[6.]

One present topic of interest is high dynamic range (HDR) image rendering. HDR image rendering is a good example in which we need the extension of CAMs to visual spatial aspects. Many algorithms have been proposed over the past decades.[7-9] Some algorithms use only global tone-mapping functions and others use local-tone mapping functions. In general, global tone-mapping functions are derived from the entire image and sometimes produce low compression failure, that is, the rendered image is too high contrast. On the other hand, local-tone mapping functions are derived from near surround and sometimes produce high compression failure. Because of eye movements, it is thought that the perceptual image is the combination of local response and integrated global responses. This paper focuses on the perception of simultaneous lightness with shadow and bright backgrounds.

The word 'lightness' is usually defined as ‘the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting’.[10] In this paper, the extended expression of the words ‘lightness’ are used as follows:

Global Lightness

The relative brightness normalized by the maximum brightness in the entire viewing angle.

Local Lightness

The relative brightness normalized by the brightness in the near-surround area.

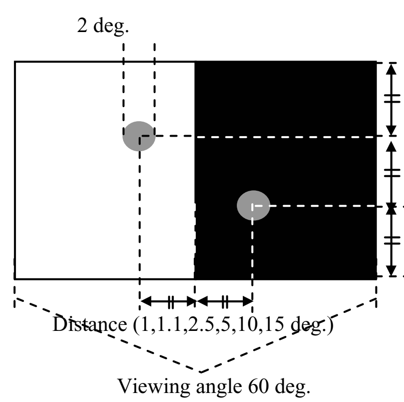

Figure 1. Schematic representation of the background and stimuli used in this experiment.

Figure 1 shows a stimulus pair on a bipartite background. This is a well-known phenomenon of simultaneous contrast. The perceived lightness of the gray on a black background matches at lower luminance than that of the gray on a white background. When calculated according to the definition, global lightness of the right gray stimulus is normalized by the left white background. On the other hand, local lightness of the right gray stimulus is normalized by the brightness in the near-surround area. The maximum brightness in the near-surround is that of the stimulus itself and then local lightness of the right gray goes to 100. The hypothesis is that the perceived lightness for complex images is a combination of local lightness and global lightness.

The purpose of this study is to investigate the contribution ratio of global and local lightness for the stimulus with several luminance levels and positions. A comparative study of the perceived lightness and the lightness predicted by an existing color appearance model was completed.

Results and Discussion

Experiment 1: Spatial Extent of Local Response

Objectives

As the first step, this experiment was designed to determine the spatial extent in which the perceived lightness is influenced. In general, HDR image rendering algorithms determine local tone by stimuli inside a certain region. It is useful for HDR image rendering algorithms to know the relation between the local response and the distance from the boundary in which the luminance of the background changes greatly.

Methods

All experiments in this paper were carried out using a SONY flat-panel LCD monitor at a viewing distance such that the width of display subtended a visual angle of approximately 60 degrees. The white of monitor was characterized to D65 and also each gray level was characterized based on this white point. Figure.1 shows the schematic representation of the bipartite background and a pair of stimuli. The left half background was set to white (130 cd/m2) and the right half background was set to black (0.35 cd/m2). The background was not changed during the experiment. A gray circle on each area of background was presented to the observer in a darkened room. The left gray circle was the reference stimulus, which was on the bright part of the background. The luminance of the reference stimulus was set to a constant value (65 cd/m2). The right gray circle was the test stimulus, which was on the dark part of the background. The number of luminance steps of the right gray (test stimulus) was 8 and the interval logarithmic. The task of the observer was to choose the gray that looks brighter.

The diameter of the gray circle was set to 2 degrees. Measurements were made with 6 different test stimulus positions. The distance from the center of gray circles to the center of background was set to 1, 1.1, 2.5, 5.0, 10 and 15 degrees. The vertical locations of two stimuli were 1/3 and 2/3 height of display to avoid the interference between the stimuli. The pair of gray circles was randomly presented to the observer by changing the luminance of test stimulus and distance from the center of background. The number of repeat trials was 10. The number of observers was five including the author. Three of observers have experiences of working in printing or photography industry for 3, 5 and 10 years. Every observer has been working for one year or more in the field of color science. Observers were instructed to view the adapting background naturally and asked to view alternately both stimuli. They were not required to fixate at any particular point.

Results

The results of this experiment are summarized in Figure 2. Figure 2 shows the luminance of the test stimulus on the black background at which the perceived lightness matches the reference stimulus (65 cd/m2) on the white background. The matching point was defined as 50% probability of observation. (5 observers * 10 iterations) Error bars indicate 95% confidence interval. As can be seen in Figure 2, the difference of the perceived lightness increases as the function of the distance. When the distance from the center becomes about 10° or more, the change in luminance decreases and the difference of the perceived lightness of each stimulus become constant. This result is in agreement with prior research and seems to be reasonable. [11]

The result indicates larger variability when the distance of the stimulus from the center of background was 5 degrees. Observers reported that the perceived lightness was changing while their focusing point was moving from the right gray to left gray. It is thought that observers could view both stimuli in the periphery when the focusing point was moving on the center of background. When the focusing point was on the stimulus, an observer could view one stimulus with their fovea while the other stimulus went away from fovea. It is possible that the time of eye movement influenced the change in the response, but there is not enough evidence in this experiment to determine the spatial and temporal integration effect.

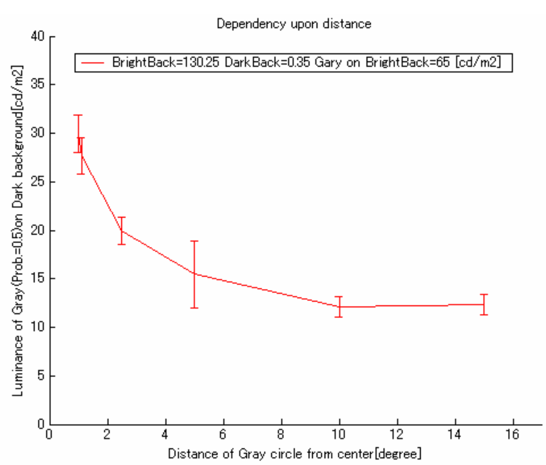

Figure 2. Distance vs. Luminance of stimulus where the perceived lightness matches.

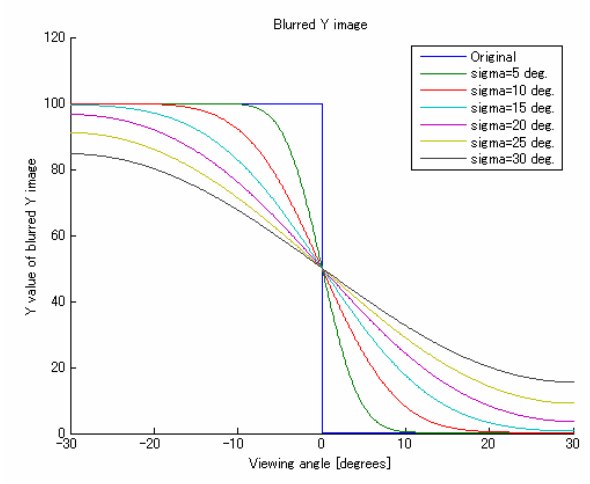

Figure 3. Profiles of the blurred bipartite images

From these data, we can say that the spatial extent in which the perceived lightness is influenced is less than 10 degrees. In other words, we can calculate the local lightness from less than 10-degree radius of surround. In iCAM, Gaussian filters are used to make a blurred image for the computation of the local response.

$$Filter = e^{-\left(\frac{x+y}{\sigma}\right)^2} \quad (1)$$

Figure 3 shows profiles of the blurred bipartite background by varying the width of filter σ. As compared with Figure 2, σ was set to 5 [deg.] in the later analysis of this paper. However it should be noted that the perceived lightness cannot be estimated only from the 5-degree radius of surround because of eye movements.

Experiment 2: Various Luminance Levels of Background and Stimulus

Objectives

The objective of the second experiment was to investigate the relationship between the global lightness and local lightness. It is of interest how to the perceived lightness changes for the variety of luminance of stimulus and bipartite background.

Methods

In this experiment, the bipartite background was used again. As Table 2 indicates, four types of background were used in this experiment. The background was not changed during each session. As with Experiment 1, the left gray circle was the reference stimulus, which was on the bright part of the background. The examined reference stimulus was 4 luminance levels at each session. The right gray circle was the test stimulus, which was on the dark part of the background. The number of luminance steps of the test stimulus was 8 and the interval was logarithmic. The pair of gray circles was randomly presented to the observer by changing the luminance of test stimulus and reference stimulus. Based on the results of Experiment 1, the position of the stimulus was set to 15 degrees from the center of the background. The task of observers and the instructions were the same as in Experiment 1.

Analysis Procedure with CIECAM02 and iCAM

The spatial arrangement of the stimulus is defined in CIECAM02. However it is sometimes applied to estimate visual perception for complex stimuli. In this paper, the CIECAM02 was used to calculate the global lightness according to the following expanded interpretation.

<u>White</u> White was usually the left, bright background, which was maximum luminance of entire viewing angle in all cases of this experiment.

<u>LA</u> The value of LA was always set to 1/5 luminance of White.

<u>Surround</u> The parameter of 'surround' was set to 'Dark' for all calculations.

<u>Yb:</u> The value Yb was set to Y of each background.

Table 1. List of the Background for Experiment 2.

	Contrast of background	
Stimulus pair	HIGH(> x10)	LOW (< x2)
Increment versus Decrement (4 level)	*Session1:* Bright part 130 [cd/m2] Dark part 0.35 [cd/m2]	-------
	Session 2: Bright part 90 [cd/m2] Dark part 0.35 [cd/m2]	
Decrement versus Decrement (4 level)	*Session 4:* Bright part 130 [cd/m2] Dark part 13 [cd/m2]	*Session 3:* Bright part 130 [cd/m2] Dark part 90 [cd/m2]

The predicted luminance in which the perceived lightness matches was calculated as follows:

1. Lightness of the left reference stimulus (J1) on the bright background was calculated by using CIECAM02 forward model.
2. Luminance of the right stimulus on the dark background in which the lightness corresponds to J1 was calculated by using CIECAM02 inverse model.
3. Lightness of the right stimulus (J2) on the dark background, in which the perceived lightness matches, was calculated by using CIECAM02 forward model.

A spatial color appearance model iCAM[6] was used to calculate the local lightness in this study since the framework of iCAM is similar to that of CIECAM02. At the first stage of iCAM, a linear adaptation transformation is performed in

CAT02 color space by using the low-pass image. The low-pass image is used as the local adapting 'white' image instead of a global 'white'. Except that the adapting white is spatially variable, this transformation is the same as that of CIECAM02. The next stage of iCAM is to convert from RGB signals into IPT opponent-color space. A spatially modulated exponent function is used and the modulation is controlled by the F_L function, which is same as that of CIECAM02. Although the matter in which the F_L factor is used in CIECAM02 and iCAM are different, these are comparable for a certain luminance level of the stimulus.

$$F_L = 0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{1/3}$$
$$k = 1/(5L_A + 1) \tag{2}$$

The F_L factor is used in CIECAM02 and lightness can be computed as follows.

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_{HPE} M_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \tag{3}$$

$$R'_a = \frac{400(F_L R'/100)^{0.42}}{27.13 + (F_L R'/100)^{0.42}} + 0.1$$
$$G'_a = \frac{400(F_L G'/100)^{0.42}}{27.13 + (F_L G'/100)^{0.42}} + 0.1 \tag{4}$$
$$B'_a = \frac{400(F_L B'/100)^{0.42}}{27.13 + (F_L B'/100)^{0.42}} + 0.1$$

$$A = [2R'_a + G'_a + (1/20)B'_a - 0.305]N_{bb} \tag{5}$$

$$J = 100(A/A_W)^{cZ}$$
$$where\ c = 0.69(average), 0.59(Dim), 0.52(dark) \tag{6}$$
$$z = 1.48 + \sqrt{Y_b/Y_W}$$

On the other hand, the conversion to IPT is given below.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = M_H^{D65} M_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \tag{7}$$

$$L' = L^{(\alpha F_L)*0.43}$$
$$M' = M^{(\alpha F_L)*0.43} \tag{8}$$
$$S' = S^{(\alpha F_L)*0.43}$$

$$\begin{bmatrix} I \\ P \\ T \end{bmatrix} = M_{IPT} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} \tag{9}$$

In this paper, the scaling factor α was set to 1.42 as lightness J of CIECAM02 corresponds to lightness I(x100) of iCAM for the stimuli on the white background in the case of Session 1.

Results

Figures 4 shows the relation between the luminance of the reference and the luminance of the test stimulus in which the perceived lightness matches each other. The matching point was defined as 50% probability of observation. (5observers 10 iterations) Error bars indicate 95% confidence interval. We can see that the effect of the dark background is larger than the prediction by CIECAM02 from Figure 4-1. In this case, the stimulus on the dark background is so-called 'unrelated color', which is isolated from the left bright background and the left stimulus. It might be possible to modify the function of CIECAM02 to correct these prediction errors within a certain dynamic range of background. However it is thought that another possible solution for 'unrelated color' is to introduce the concept of local lightness.

In session 3, the prediction of CIECAM02 was corresponding to measurements very well.

In session 4, the dynamic range of the bipartite background was set to higher value than in session 3. In consideration of the stimulus pair becoming both decrements, the luminance of the bipartite background was set to 130 cd/m2 and 13 cd/m2. We can see again gaps between the CIECAM02 prediction and measurements in Figure 4-2. This gap is not so large but seems to be significant in comparison with 95% confidence interval. One may say that the gap between the prediction and the perceived lightness is larger when the dynamic range of the background increases from these results.

Now, the lightness for the stimulus in each case was computed with iCAM and CIECAM02. If the predictions were perfect, the calculated lightness of gray on the bright background should equal the calculated lightness of gray on the dark background. iCAM has a free parameter D, which is used in a linear adaptation transformation as adaptation degree. The lightness was calculated for two cases D=1 and D=0. We can recognize from Figure 5 that iCAM tends to overestimate the background effect and CIECAM02 tends to underestimate it.

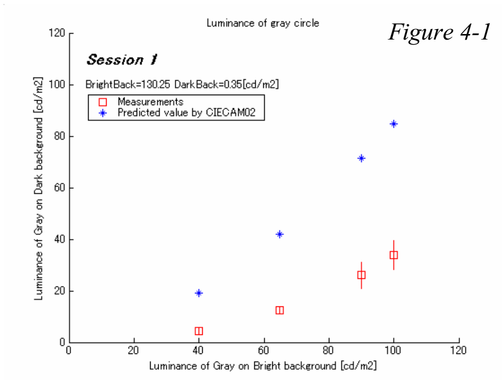

Figure 4-1

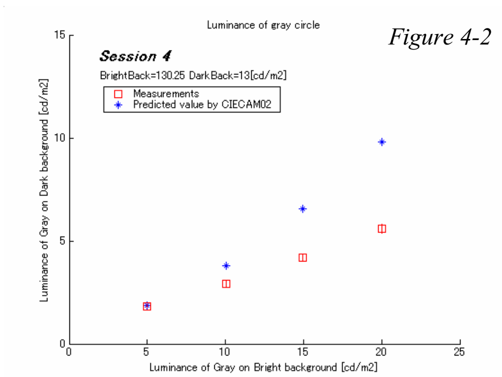

Figure 4-2

Figure 4. Results of lightness matching

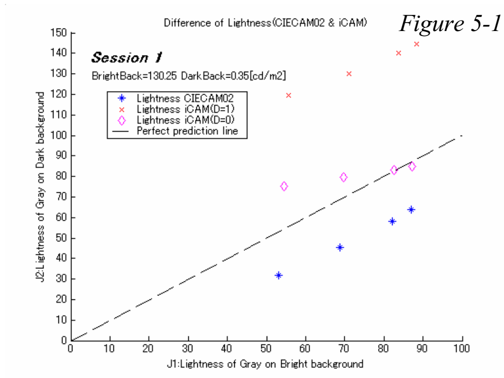

Figure 5-1

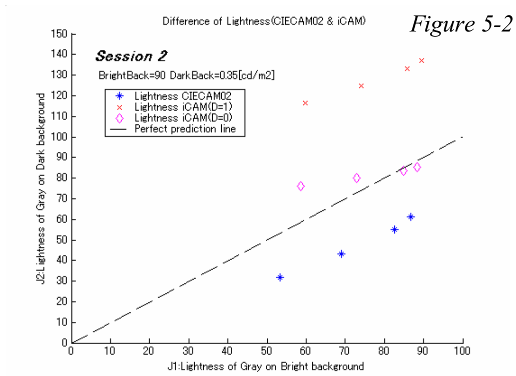

Figure 5-2

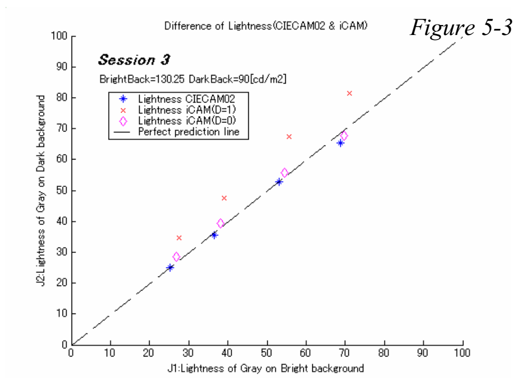

Figure 5-3

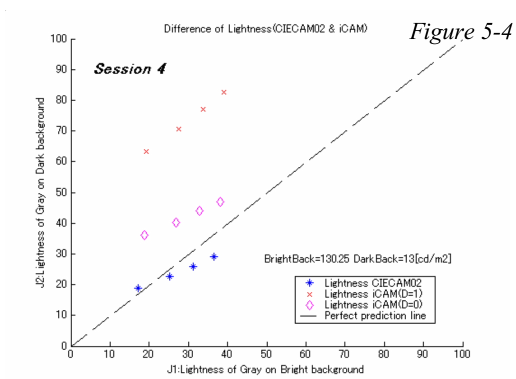

Figure 5-4

Figure 5. Prediction by CIECAM02 and iCAM

Ratio of Local Lightness and Global Lightness

Let us assume that the perceived lightness exists between global lightness computed by CIECAM02 and local lightness computed by iCAM. A simple formula was introduced in order to estimate the contribution ratio of local lightness and global lightness.

$$Jp = \alpha \times Jlocal + (1-\alpha) \times Jglobal \qquad (10)$$

where

Jp represents perceived lightness. *Jlocal* represents local lightness computed by iCAM (D=1)

Jglobal represents global lightness computed by CIECAM02.

α represents contribution ratio.

Figure 6 shows the relation between *Jlocal and Jglobal* of stimuli on the left bright background. Here, as for stimuli on the left bright background, the approximation *Jlocal* = *Jglobal* is introduced to simplify the following analyses.

According to the formula (10) and this approximation, we can get formula (11) and (12). *J1* represents the lightness of the stimulus on the left bright background, where the local lightness equals to the global lightness in this experiment. On the other hand, *J2* represents the lightness of the stimulus on the right dark background.

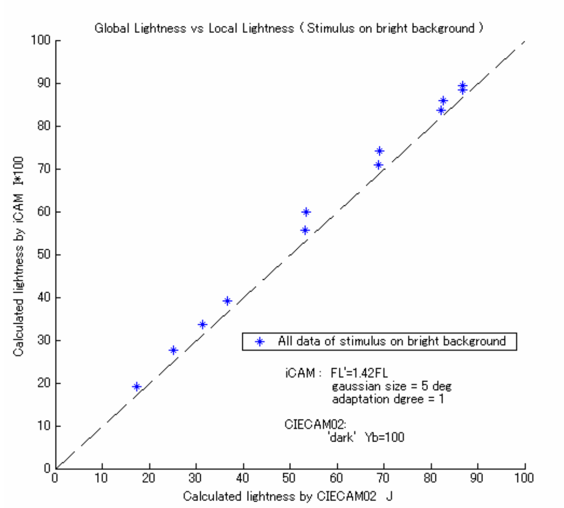

Figure 6.

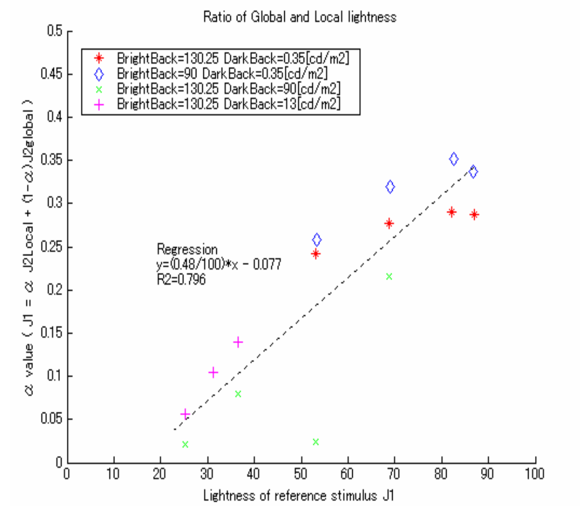

Figure 7.

$$J1p = J1global \quad (11)$$

$$J2p = \alpha \times J2local + (1-\alpha) \times J2global \quad (12)$$

The value of α was calculated to become *J1p* = *J2p* from measurements of session 1-4 and was plotted in Figure 7. Figure 7 shows that the value of α increases according to the lightness of the reference stimulus *Jp*. The next expression is obtained when assuming that the relation between *Jp* and α is linear from Figure 7.

$$\alpha = a \times Jp - b \quad (13)$$

Plugging formula (13) into formula (10), we can get the following formula.

$$Jp = \frac{Jglobal - b \times (Jlocal - Jglobal)}{1 - a \times (Jlocal - Jglobal)} \quad (14)$$

This is an expression that corrects the perceived lightness in this experiment. When the local lightness is greater than the global lightness, for instance, in the case of the stimulus on the dark part, the corrected lightness is larger than the global lightness according to the expression (14). On the other hand, when the difference between local and global lightness is small, the perceived lightness is close to the global lightness. By using the new formula (14), lightness of all stimuli were calculated and plotted on Figure 8. Of course, the function that expresses the effect of the background already exists in CIECAM02. The relation to this modification remains as a matter to be discussed further. And more investigation must be required to build a general model. It is possible that the ratio of the local and global lightness is different from that in this experiment when the dynamic range of background increases. However, the introduction of local lightness gives a good account of the effect of dark background in this experiment.

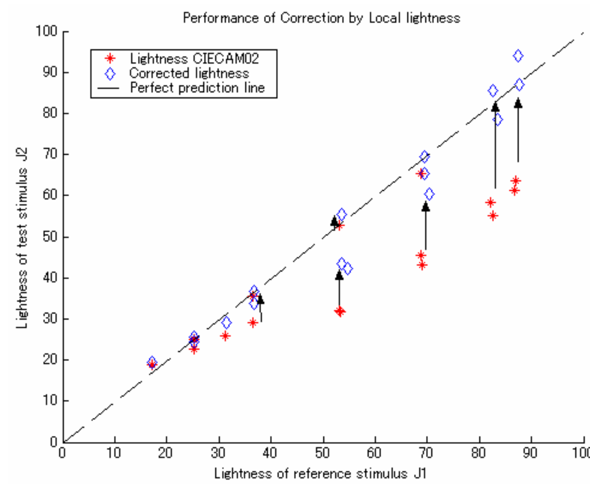

Figure 8.

Conclusion

We have evaluated the spatial extent in which the perceived lightness is influenced under the simultaneous binocular conditions by using a bipartite background. The results of Experiment 1 shows that the spatial extent responsible for local response is less than 10 degrees. The evaluation of the perceived lightness was performed at the various luminance level and contrast of the bipartite background in Experiment 2. When the dynamic range of the background was large, CIECAM02 prediction for the effect of dark background was lower than measurements. A lightness perception model was introduced to explain this prediction error. The factor of the difference between global and local lightness could correct the prediction error in this experiment. The spatial extent information could be used in combination with the local/global contribution ratio to build a spatial appearance model like iCAM for HDR image rendering applications.

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Biography

Hiroshi Yamaguchi received his BS and MS degrees in physics from Waseda University in 1990 and 1992. He joined Fuji Photo Film in 1992. Since then, he has been working in digital color image processing. He has developed some photographic printers such as Pictrography and Frontier. He is a visiting scientist at Rochester Institute of Technology, and a member of the IS&T.