OPTICAL REVIEW Vol. 7, No. 3 (2000) 260–265

Luminance-Type Additive Mechanism Produces Shading

Shoji SUNAGA,[1] Satoshi SHIOIRI[2] and Hirohisa YAGUCHI[2]

[1]*Department of Visual Communication Design, Kyushu Institute of Design, 4-9-1, Shiobaru, Minamie-ku, Fukuoka, 815-8540 Japan,* [2]*Department of Information Image Science, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522 Japan*

(Received December 20, 1999; Accepted February 4, 2000)

It has been reported that the luminance mechanism mediates shadow perception of binary images. We evaluated the luminance additivity law to determine whether shading, which is produced by gradual intensity changes, is mediated by luminance or brightness using pictures with tones: two still lives and a painting. They were depicted by two colors—a reference color and a test color. The reference color was white with a constant luminance profile, and the test color was a mixture of red and green in various proportions. The observer's task was to adjust the luminance of the test color in order that the impression of depth due to shading just disappeared (shading disappearance setting), where the intensity that produced the shading supposed to be equated between the test and the reference colors. The results show that the luminance additivity law holds for shading disappearance settings. This suggests that shading perception is based on luminance or a luminance-type additive mechanism as well as shadow.

Key words: luminance, brightness, shading perception, additivity, isoluminace, low spatiotemporal frequency

1. Introduction

In visual processing, appropriate intensity differences can be perceived as shading or shadow which produce a vivid sensation of three dimensional shapes.[1–3] Livingstone and Hubel demonstrated that the three dimensional perception disappeared or was weakened when stimulus pictures were presented by two colors with which there is no luminance difference.[1,2] For example, they found the depth from shading disappeared when the relative intensity of red and green reached a certain balance point. They concluded that the two colors had equal luminance at the balance point and that the depth from shading was lost at equal luminance.

However, the balance point is not necessarily at equal luminance. It is known that there is an equal brightness point that differs from equal luminance. Shioiri and Cavanagh asked whether it was at equal luminance or at equal brightness that the impression of depth from shadow disappeared.[4] They examined the luminance additivity to distinguish the mechanism based on luminance from that based on brightness. Their results showed that the luminance additivity law of color mixtures held when the observer adjusted the balance of two colors in a binary shadow figure so that the shadow disappeared. This result indicates that shadow perception is mediated by the luminance or a luminance-type additive mechanism.

Although Shioiri and Cavanagh used a figure of a three-dimensional object (a cup) as the stimulus, this was a binary image. Their stimulus, therefore, contained relatively high spatial frequency components or sharp edges between test and reference, and an underlying edge detection mechanism contributed to their results. Since sharp edges are suggested to be determined by luminance differences,[5] their results may be interpreted by this mechanism. Although their data suggest that the underlying mechanism for form perception is the luminance mechanism, they do not provide information on the form perception without sharp edges or images with gray levels.

In the present paper, we extended their study by investigating whether shading is mediated by luminance or brightness for stimuli which are familiar pictures with tones (as expressed by a gradual change between two colors) which do not contain much high spatial frequency. We measured a balance point of two colors in shading figures so that the shading disappeared (shading disappearance point) and examined the luminance additivity law of the color mixtures. If shading perception is based on the luminance or a luminance-type additive mechanism, it is expected that the luminance additivity law would hold for the shading disappearance settings as the minimum flicker settings.[6] If, on the other hand, shading perception is mediated by a process similar to that underlying brightness perception, the additivity law should fail as direct brightness matching.[7–9]

2. Methods

2.1 *Apparatus and Stimuli*

We used a computer graphic system with a color monitor. The system could display colors with 8-bit resolution for each phosphor. The output of each primary was linearized with software after careful measurements of the display luminance. The change of the luminance generated on the monitor was discrete, and its minimum step was 0.17 cd/m^2 or less for the red phosphor and 0.57 cd/m^2 or less for the green phosphor. The test field, in which color the observer varied, contained only red and green. We used the three shading figures shown in Fig. 1 as the

E-mail: sunaga@kyushu-id.ac.jp

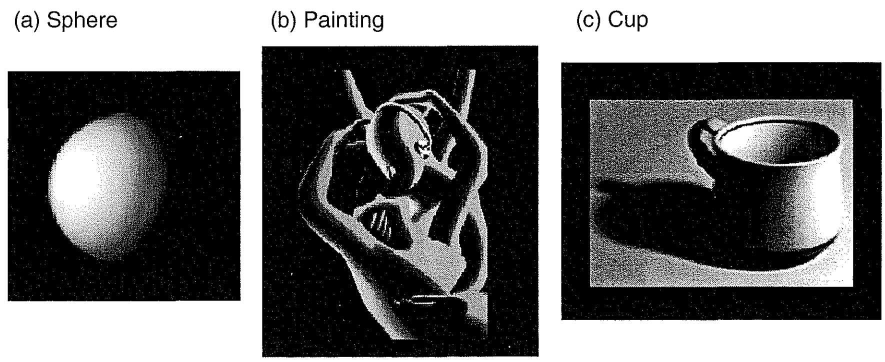

Fig. 1. The stimuli used in this experiment, a plaster sphere that was illuminated by a single light source from the left side (a), part of a painting drawn by Mark Kostabi (b), and a tea cup that was illuminated by a single light source from the right side (c).

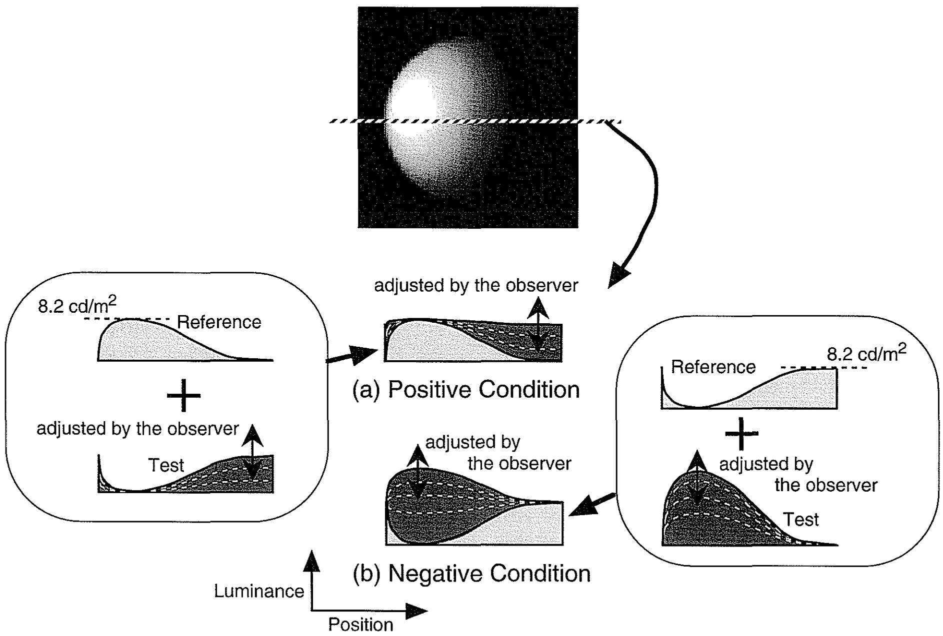

Fig. 2. The luminance profile of the sphere image. In one condition (a), the luminance profile of the reference color is the positive image of the original black and white digitized picture and that of the test color is the negative of the original image (positive condition). In the other condition (b), the luminance profile for reference and test are exchanged, positive for test and negative for reference (negative condition). The luminance of the test color was varied by the observers.

stimuli. Their three dimensional structure is easily seen by shadings and/or shadows. Figure 1(a) is an image of a sphere that is illuminated by a single light source, (b) is a part of a painting by Mark Kostabi, and (c) is an image of a cup that was illuminated by a single light. Figure 1(a) and (b) did not have background. The stimuli sizes were 10×10 deg in visual angle for the sphere, 10×14.5 deg for the painting and 14.5×10 deg for the cup. The monitor was located 37 cm in front of the observer, and 10 deg of visual angle corresponded to 180 pixels on the monitor.

There were two conditions for each stimulus in the experiment. Luminance profiles for these conditions are shown in Fig. 2 for the sphere. In the first condition (Fig. 2(a)), the luminance profile of the reference color was the positive image of the original figure (lighter area in Fig. 1 is the reference color), and that of the test color was the negative image of the original figure (the darkest area in Fig. 1). If the test and the reference are the same color with the same luminance, the display will be uniform. Since the reference color was the positive image of the original figure in this condition, we labeled this condition the positive condition. In the positive condition, when the intensity of the reference color was sufficiently larger than that of the test color, a three dimensional structure from shading could be seen. In the second condition (Fig. 2(b)), the luminance profile of the reference color was the negative image of the original figure, and that of the test color was the positive image (the negative condition). In the negative condition, the three dimensional structure from shading could be correctly interpreted when the intensity of the test color was sufficiently larger than that of the reference color.

The luminance of the reference color was fixed at 8.2 cd/m^2 and its CIE *xy* color coordinates were 0.28, 0.30 (white) in both positive and negative conditions. The test color was red, green or a mixture of the two (the color of the red or the green phosphor of the monitor). The CIE *xy* coordinates of the red were (0.62, 0.35) and those of the green were (0.27, 0.61). The red-to-green luminance ratio of the mixtures used was 1:0 (pure red of the phosphor), 1.5:1, 1:1.7, 1:3.5, 1:7, 1:18, or 0:1 (pure green of the phosphor).

2.2 Procedure

There were three tasks in the experiment. The first task was the shading disappearance setting, and this was applied for both positive and negative conditions. In the positive condition, shading could be seen in the test color field when the radiance of the test color was sufficiently darker than that of the reference color. The observer's task was to adjust the radiance of the test color in order that the impression of depth due to shading in the test field just disappeared (shading disappearance setting). We assumed that the response of the test color was equal to that of the reference color in the mechanism that mediates shading perception at the shading disappearance point. The initial luminance of the test color was set to the darkest level on the display in the positive condition or was sufficiently brighter than the reference color in the negative condition so that the observer could easily see the three dimensional structure of the shading figures.

The second was the minimum flicker setting and the third task was equal brightness matching. These tasks were performed in the same figures to compare directly with the shading disappearance setting. In the flicker setting, the positive and negative figures were alternatively presented at 16.5 Hz. In other words, the reference color and the test color were alternated. The observers were instructed to minimize flicker sensation by adjusting the radiance of the test color. The relationship between the two colors used is referred to isoluminant by definition. Heterochromatic brightness matching was performed in both the positive and negative shading figures as was shading disappearance settings. In this task, the observer adjusted the radiance of the test color to equate the impression of brightness between the non-shadow region and the shadow region in the stimulus.

Each experimental session began following five minutes of adaptation to the dark. The stimulus was presented repeatedly for 1 s with 2 s of dark blank intervals (the blank was the same luminance as that of the background). The observer was able to vary the radiance of test color during the blank interval. He viewed the stimulus binocularly with his natural pupils. The observer was asked to fixate the center of the stimulus, although there was no fixation point. The test color varied randomly from setting to setting. In a single session, observers completed 4 settings for each color mixture of each task, and each observer ran two sessions. Three males (CM, SS and SSU) served as observers; two of them were authors. These observers had normal color vision and normal or corrected-to-normal acuity.

3. Results

Our primary interest is whether or not the luminance additivity law holds for each task. Results for each stimulus are analyzed with conventional plots for an additivity test. Figure 3 shows the adjusted test luminance in the positive conditions in a red and green color space. The horizontal and vertical axes are scaled so that the setting for pure red and pure green of the phosphor becomes 1.0 for each task. Filled circles represent the settings for the shading disappearance, open squares those for the minimum flicker, and open triangles those for brightness matching. Each point is the average of eight settings. The error bar represents ± 1 standard error, which is shown when it is larger than the symbol. Since the luminance of the test color was varied with a constant chromaticity for each color mixture (red/green=constant), the setting point is on a radial from the origin. Figure 4 shows results for the negative condition plotted in the same way as in Fig. 3.

If the additivity law holds for a task, the data points should be aligned on a straight line with the slope of -1. At first glance, in Fig. 3, the data points are plotted around the diagonal line of the additivity function for shading disappearance settings and minimum flicker settings for all observers and all figures. In contrast, the data points for brightness matching tend to deviate from the diagonal line of the additivity function, and also from the other two settings. In particular, additivity failure is remarkable for the sphere image for all observers. Similar failures are found for the brightness matching of the cup and the painting, although the magnitude of failure is smaller. The results in the negative condition shown in Fig. 4 are similar to those in the positive condition. Clear additivity failure is found for brightness matching and the amount is remarkable for the sphere. These results suggest that the luminance additivity holds for shading disappearances and minimum flickers independent of stimuli or observer, whereas it fails for direct brightness matching. However, the shading disappearance settings do not always agree with the minimum flicker settings, tending to be below the minimum flicker in the positive condition of observer CM and in the negative condition of all observers.

To examine the differences among the three settings, a one-way analysis of variance was performed with three levels of the task variable for the independently. The F value was calculated for each combination from the three tasks in each of the positive and negative conditions. The results for the positive conditions indicate that the shading disappearance setting did not differ significantly from the minimum flicker setting for all stimuli [$F(1, 28)=0.47$ for the sphere, $F(1, 28)=3.56$ for the painting,

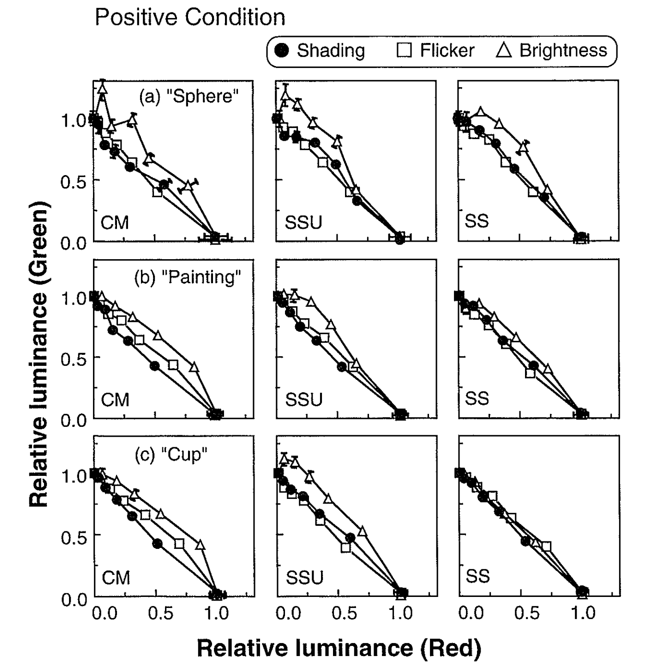

Fig. 3. Results in the positive condition for each observer for each stimulus. Closed circles represent the shading disappearance setting, open squares the minimum flicker setting and open triangles the brightness matching. The values of the red or green settings are normalized so that the radiance of the red or green is 1.0 when only that colors is used for each task. Error bars denote ± 1 standard error. If luminance additivity holds, the line connecting data points should have a slope of -1.

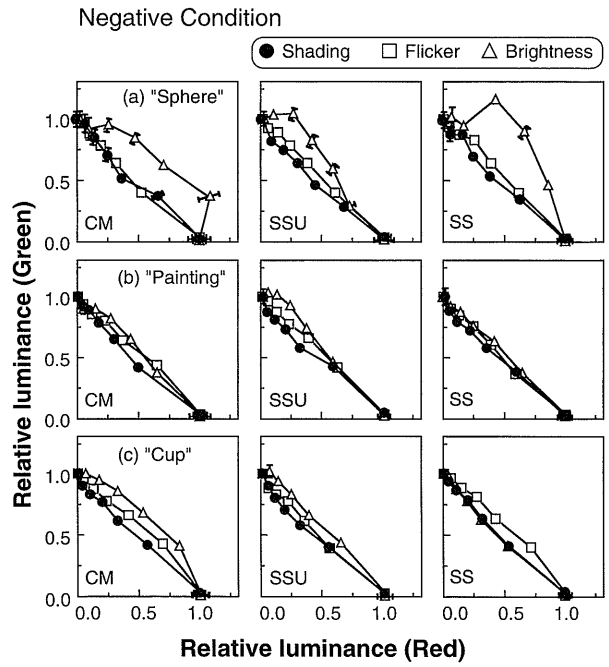

Fig. 4. Settings for the negative condition plotted in the same way as in Fig. 3.

and $F(1, 28)=3.58$ for the cup, all insignificant, $p>0.05$]. On the other hand, the brightness matching differed significantly from the shading disappearance setting [$F(1, 28)=38.21$ for the sphere, $F(1, 28)=45.03$ for the painting, and $F(1, 28)=37.12$ for the cup, all $p<0.001$], and from the minimum flicker setting [$F(1, 28)=60.74$ for the sphere, $F(1, 28)=34.98$ for the painting, and $F(1, 28)=19.37$ for the cup, all $p<0.001$]. These results suggest that the shading disappearance settings was closer to those of minimum flicker settings than to those of brightness matching in terms of the additivity feature.

The results in the negative condition are somewhat different from those in the positive condition. The shading disappearance setting significantly differed from the brightness matching [$F(1, 28)=37.63$ for the sphere, $F(1, 28)=36.53$ for the painting, and $F(1, 28)=21.86$ for the cup, all $p<0.001$] as in the positive condition. However, the shading disappearance setting also significantly differed from the minimum flicker setting for all stimuli [$F(1, 28)=8.04$ ($p<0.05$) for the sphere, $F(1, 28)=23.33$ ($p<0.001$) for the painting, and $F(1, 28)=15.93$ ($p<0.001$) for the cup]. The shading disappearance setting differed both from minimum flicker setting and from brightness matching. Indeed, unique characteristics of the shading setting are seen in Fig. 4. The result of the shading setting shows slight additivity failure of enhancement (i.e., less intensity is needed in a mixture than in each component color), which is not seen for the other settings in either condition. These results may indicate that different mechanisms determine the minimum flicker and the shading disappearance.

The fact that shading perception is independent on brightness perception leads one to suspect that shading might be seen when the shading area looks brighter than non-shading areas and shading might not be seen when the shading area looks darker. We replotted the data to compare the shading disappearance settings and the brightness matches, and the results for the positive and negative conditions are shown in Figs. 5 and 6, respectively. The horizontal and vertical axes in these figures are scaled so that luminance of minimum flicker settings for the pure red and for the pure green is 1.0. Filled circles represent the settings for shading disappearance and open triangles those for brightness matching. The error bar represents ± 1 standard error for the settings of each color. Figures 5 and 6 show that the radiance of the test color with which shading disappeared was larger than that for equal brightness in both conditions except for two cases (results for observers SSU and SS in the positive condition with the sphere). This indicates that in the positive condition, shading was seen in the test field even when the field was perceived to be brighter than the reference (shaded zones in Fig. 5). In the negative conditions, on the other hand, there are some zones in which shading was not seen in the reference field even when the reference color was perceived to be darker than the test (shaded zones in Fig. 6). As we expect, the existence of these zones indicates that shading perception is independent from brightness perception.

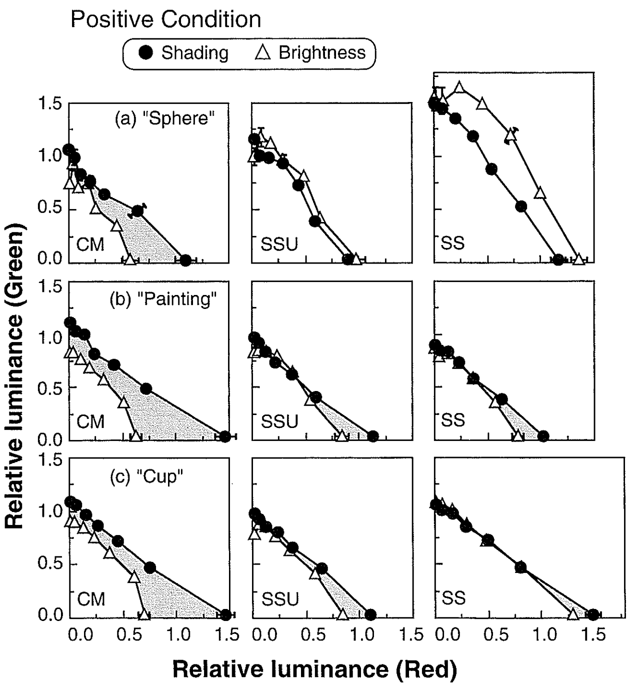

Fig. 5. Shading disappearance setting and brightness matching relative to minimum flicker setting for the positive condition for each observer and stimulus. Closed circles represent the shading disappearance setting and open triangles represent brightness matching. The values of the red or green settings are normalized so that the radiance of the red or the green is 1.0 when that color is used alone for the minimum flicker. Error bars denote ± 1 standard error. The shaded region indicates that the range of radiance of the test color was brighter than the reference but was perceived as shading.

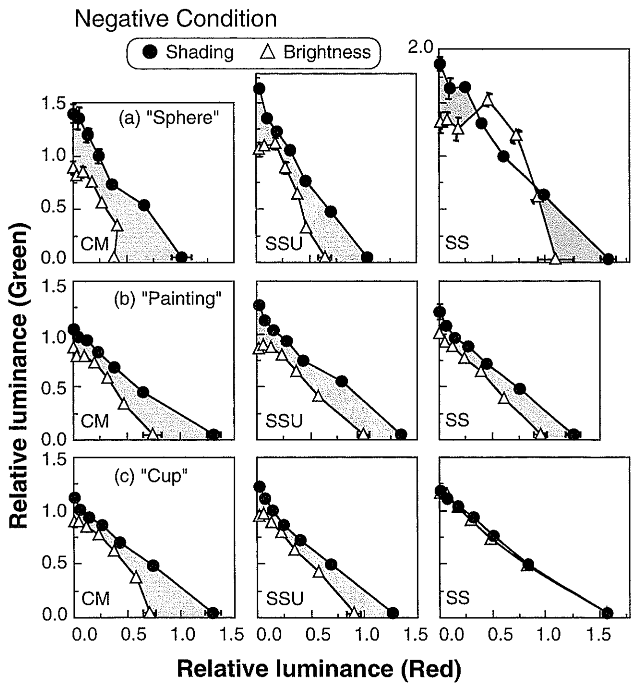

Fig. 6. Shading disappearance setting and brightness matching relative to minimum flicker setting for the negative condition plotted in the same way as Fig. 5. The shaded region indicates that the range of radiance of the reference color was darker than the test but was not perceived as shading.

Another important finding shown in Figs. 5 and 6 is that the absolute values of the settings are systematically different between the flicker and shading settings. The settings for shading disappearance tend to be above the (imaginary) line connecting (1, 0) and (0, 1) on which flicker settings would be plotted. More test color was needed for shading settings than equal luminance to the reference color.

4. Discussion

The present study shows that the additivity law roughly held for the shading disappearance setting in the figure with tones as it did for the minimum flicker, whereas it failed for the brightness matching. A statistical test showed that shading disappearance setting is not different from minimum flicker, whereas it is different from brightness matching in the positive condition when they were compared in normalized values. In the negative conditions, however, the same test showed that shading disappearance is significantly different from the minimum flicker setting as it is from brightness matching. The difference is due to the slight additivity failure of the enhancement type for the shading settings, which are in the opposite direction of the additivity failure of the reduction type seen for brightness matching. In addition,

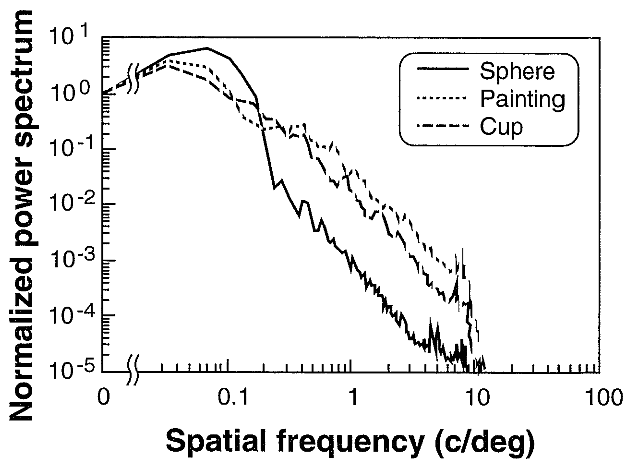

Fig. 7. Spatial frequency components contained in each shading figure. The power spectrum is normalized so that the d.c. level (i.e., spatial frequency = 0) becomes 1.0 for each figure.

the absolute values of settings were different between the flicker and shading settings. More test color was needed for shading settings than equal luminance to the reference color.

These results suggest that two or three different mechanisms are involved in the three tasks. First, it is clear that brightness matching is mediated by a non-additive mechanism, which perhaps has input from opponent color mechanisms.[7–9] Second, the flicker perception is mediated by the luminance mechanism by definition. Third, the mechanism that mediates shading information might be different from the luminance mechanism. Although we showed that the mechanism is, at least roughly, additive consistently to the luminance mechanism, differences between flicker and shading settings were also found. These differences may be because they are processed by different mechanisms. There are two possible dichotomies for the physiological pathways for achromatic signals. One is the dichotomy of the Parvo- and Magno-pathways. Although there is general agreement that flicker and therefore luminance is mediated by the Magno-pathways, slower and detailed achromatic information is likely to be mediated by the Parvo-pathway.[10] In our experiments shading settings were performed in slow stimulation, and results of these settings may be based on signals in the Parvo-pathway. The shading perception may be based on Parvo achromatic signals. A problem with this interpretation is that we have to assume that the Parvo-pathway is sensitive to low spatial frequency information for shading in the stimulus.

The other is the dichotomy of the X-type and Y-type M-pathways. Two different types of magnocellular cells, which are different in temporal characteristics have been reported.[11] The first type, the X-type M-pathways shows longer latency than the second, the Y-type M-pathway. It may be the case that the shading perception is based on the X-type M-pathways and flicker perception is based on the Y-type M-pathways. A problem with this interpretation is that we have to assume that the Magno-pathway is sensitive to the low temporal frequency stimulation in our experiment. Either of the dichotomies may or may not be appropriate to explain the difference between the flicker and shading perception.

There may be other explanations for the differences between the flicker and shading settings such as the effect of three dimensional structures of objects.[12–14] However, these are not discussed here since we found there is no simple explanation of our results based on these effects. We cannot say which of the two physiological explanations above or other explanations are the cause of the difference between the flicker and shading settings because our data are limited. Only further investigation can solve the issue.

The pronounced influence of the stimulus images was seen in brightness matching, whereas results for the shading disappearance and the minimum flicker are rather independent from the stimuli. Larger additivity failure was found for the sphere image than for the other figures. A possible explanation of the results is that spatial frequency content in the stimulus affects the magnitude of additivity failure for brightness matching. Yaguchi reported that large additivity failure was observed at relatively low spatial frequencies ($0.1 \sim 2.0$ c/deg), whereas the magnitude of additivity failure was less or null at higher spatial frequencies.[15] To examine whether the different amount of additivity failure among the figures used was due to the difference in their spatial frequency content, we evaluated the content in each figure by Fourier analysis. The spatial frequency components contained in each stimulus figure are shown in Fig. 7. The horizontal axis of Fig. 7 shows the spatial frequency, and the vertical axis the power spectra normalized at the spatial frequency of zero. The power spectrum of the sphere in Fig. 7 was quite different from those of the painting and the cup. The sphere contained more lower and less higher spatial frequency content than the others. Since additivity failure is larger for lower spatial frequency,[15] our results of larger additivity failure for the sphere can be attributed to the greater amount of lower spatial frequency content of the image.

In conclusion, we found that the shading perception is mediated by the luminance-type additive mechanism as is the flicker perception whereas the brightness perception is mediated by the non-additive mechanism. We also found the difference between the shading and flicker perception. This suggests that the form perception with low spatiotemporal stimulation may be mediated by a mechanism that is different from the luminance characterized by flicker perception.

References

1) M. Livingstone and D. Hubel: J. Neurosci. **7** (1987) 3416.
2) M. Livingstone and D. Hubel: Science **240** (1988) 740.
3) P. Cavanagh and Y. G. Leclerc: J. Exp. Psychol. Human Percept. Perform. **15** (1989) 3.
4) S. Shioiri and P. Cavanagh: J. Opt. Soc. Am. A **9** (1992) 1672.
5) R. M. Boynton and P. K. Kaiser: Science **116** (1968) 366.
6) H. E. Ives: Philos. Mag. **24** (1912) 845.
7) P. K. Kaiser and G. Wyszecki: Color Res. Appl. **3** (1978) 177.
8) H. Yaguchi and M. Ikeda: Vision Res. **23** (1983) 1711.
9) Y. Nakano, M. Ikeda and P. K. Kaiser: Vision Res. **28** (1988) 799.
10) R. L. DeValois and K. K. DeValois: Vision Res. **33** (1993) 1053.
11) E. Kaplan and R. M. Shapley: J. Physiol. **330** (1982) 125.
12) A. Gilchrist, S. Delman and A. Jacobsen: Percept. Psychophys. **33** (1983) 425.
13) D. C. Knill and D. Kersten: Nature (London) **351** (1991) 228.
14) E. H. Adelson: Science **262** (1993) 2042.
15) H. Yaguchi: J. Opt. Soc. Am. A **4** (1987) 540.