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Effect of Spatial Frequency on Equal-Luminance Point for the Mechanism of Shape from Shading*

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We examined 1) whether the perception of shape from shading is based on luminance or brightness by testing the additivity law, and 2) whether the spatial frequency contents in the stimulus affect on the spectral sensitivity. We measured the relative radiance at which shading disappeared in a simple shading figure. Results showed that 1) the additivity law holds for shading disappearance settings and that 2) the sensitivity for green to white decreased as higher spatial frequencies in the figure decreases. These results suggest that the perception of shape from shading is based on a luminance type additive mechanism and that the spectral sensitivity of the mechanism varies depending on spatial frequency.

Key words: perception of shape from shading, form perception, luminance, brightness, luminance additivity, spatial frequency, spectral sensitivity

1. Introduction

Luminance, which is estimated by the flicker photometry, is known as the intensity dimension of the achromatic form pathway. This is supported by the fact that strength of the edge generated by two colors is minimized at equal luminance (minimally distinct border or MDB method).[1)] However, since flicker photometry is based on high temporal frequencies and MDB is based on high spatial frequencies, it is not clear that luminance is the intensity dimension of the achromatic form pathway at the low spatiotemporal frequency region. On the other hand, there is another intensity dimension known as brightness, which is estimated by direct brightness matching. The equal brightness point between different colors does not agree with the equal luminance point.[1)] Since the stimuli used for brightness matching are normally presented as a bipartite field with long duration, they contain low spatial and temporal frequencies. This may indicate that brightness is the intensity dimension of the achromatic form pathway at the low spatiotemporal frequency region.

To examine which of luminance or brightness is the intensity dimension of form perception, Shioiri and Cavanagh measured the relative radiance of two colors to determine where the impression of subjective contours and depth due to shadow was minimal. Their data suggested that the achromatic form pathway for relatively low spatiotemporal frequencies is based on the luminance mechanism.[2)] However, systematic investigation is desired because they varied stimulus spatial frequency only within a limited range.

We used perception of three dimensional shape or depth from shading in figures whose spatial frequency contents were systematically controlled. The stimulus figure was a shading figure in two colors (Fig. 1). Shading could be seen when the radiance of either color was sufficiently darker than that of the other. The observer's task was to adjust the relative radiance in order that the impression of depth due to shading disappeared (we call this setting the shading disappearance setting). At the shading disappearance point, the intensities of the two colors are supposed to be equal for the mechanism that mediates the perception of shape from shading. We tested the additivity law of color mixture for the shading disappearance point to distinguish the mechanism based on luminance from that based on brightness. If the luminance mechanism mediates shading perception, the additivity law will hold for shading disappearance settings. In contrast, if the brightness mechanism mediates shading perception, the additivity law should fail.[3)] Results showed that the shading disappearance setting obeyed the additivity law. This suggests the perception of shape from shading is based on luminance or a luminance-type additive mechanism.

We also investigated the effect of spatial frequency for the shading disappearance setting. The shading technique allows us to measure the equal intensity point for form perception at the low spatiotemporal frequency region, at which both flicker photometry and MDB method cannot be applied. It was found that the sensitivity of green to white declined as high spatial frequencies in the stimulus figure decreased. This suggests that there is no constant equal luminance point for all spatiotemporal frequency regions.

2. Method

2.1 Stimuli and Apparatus

We used a computer graphic system with a color monitor. The system could display colors with 8-bit resolution for each phosphor. A shading figure shown in Fig. 1 was used as the stimulus and the size was either 2°, 10°, 20° or 30°. The shading figure consisted of a reference color and test color, whose luminance profiles were cumulative Gaussian distribution functions along the horizontal axis (constant along the vertical axis). The space constant (the

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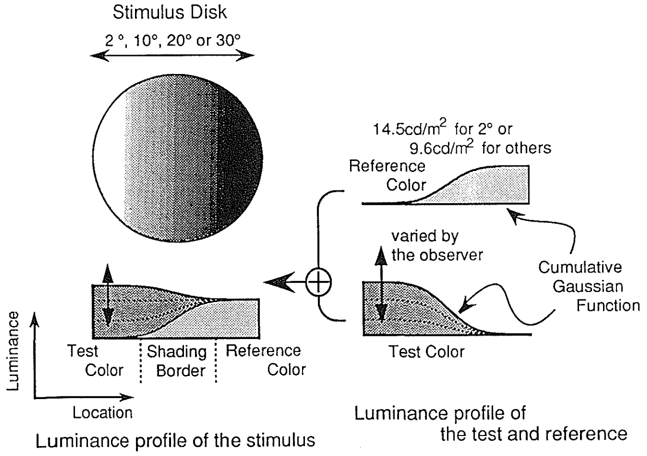

Fig. 1. The stimulus used in the experiment. The luminance profile of the reference and the test colors was a cumulative Gaussian distribution function. The space constant was the same for the reference and the test, but the slope was in opposite.

standard deviation of the function) was the same for the reference and the test colors but the slope was in the opposite for the two colors. When either color was sufficiently darker than the other, shading based on the gradual change between the two colors could be seen. The space constant of the function varied to change the spatial frequency contents in the stimulus. The space constant was 4, 8, 12, 16 or 20′ for the 2° disk; 20, 80 or 100′ for the 10° disk; 200′ for the 20° disk; and 300′ for the 30° disk. For the larger space constant (or lower cutoff frequency), the shading border between the reference color and the test color was more blurred. The 1% cutoff spatial frequency varied from 7.2 to 0.1 c/deg according to the change of the space constant.

We used white with CIE xy chromaticity coordinates of 0.28, 0.30 as the reference color. The luminance of the reference was fixed at 14.5 cd/m^2 for the 2° stimulus and 9.6 cd/m^2 for the other stimulus. The test color was red, green, or a mixture of them and the luminance of the test color was varied with constant chrominance by the observer. Red and green here represent the color of the red and the green phosphors of the CRT display, and their CIE xy coordinates were 0.62, 0.35 for red and 0.27, 0.61 for green, respectively. The red-to-green luminance ratio of the mixture used was either 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). The background of the shading figure was dark gray with a luminance of 0.4 cd/m^2.

2.2 *Procedure*

There were three different tasks in the experiment: Finding the shading disappearance setting, the minimum flicker setting, and the brightness matching. In the shading disappearance setting, the observer adjusted the radiance of the test color in order that the impression of depth due to shading was minimized or disappeared completely. We assume that the intensity of the test color is equal to that of the reference color for the mechanism that mediates shading perception at the shading disappearance point.

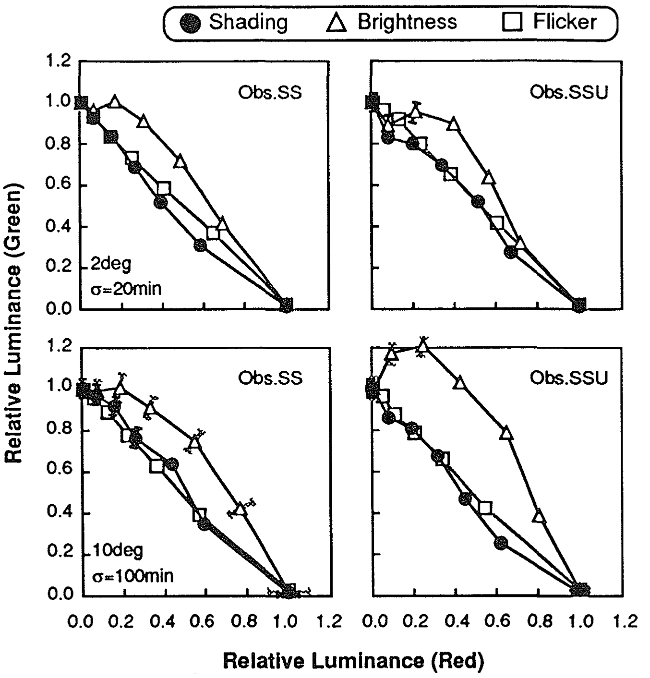

Fig. 2. Settings obtained for the 2° stimulus with 20′ space contrast and the 10° stimulus with 100′. Filled circle represents the shading disappearance setting, open square represents the minimum flicker setting, and open triangle represents the brightness matching setting. The values of the red or green settings are normalized so that the radiance of the red or the green is 1.0 when the red or the green is used alone for each task. The error bars denote ±1 standard error.

In the minimum flicker setting, the positions of the reference color and the test color in the stimulus figure were alternated at 16.5 Hz, and the observer minimized the flicker sensation by adjusting the radiance of the test color. In the brightness matching, the observer adjusted the radiance of test color to equate the impression of brightness between the test and reference colors across the shading border.

In addition to the shading disappearance setting, we measured detection thresholds for three dimensional shape or depth from shading. The observer's task was to adjust the luminance of the test color in order that three dimensional shape from shading was just perceived either in the test color or in the reference color. We call the task the setting of just appearance of shading.

Each experimental session began following five minutes of dark adaptation. The stimulus was presented repeatedly for 1 s followed by a 2 s of dark interval (0.4 cd/m^2). The observer fixated the center of the stimulus binocularly with natural pupils. The test color varied randomly from trial to trial, and the observers completed 4 settings for each color mixture of each task in a single session. Each observer ran 2 or 4 sessions for each condition.

Five males served as observers. All observers had normal color vision and normal or corrected-to-normal acuity.

3. Results and Discussion

Results for each condition are analyzed by the conventional plots for additivity tests (the horizontal axis repre-

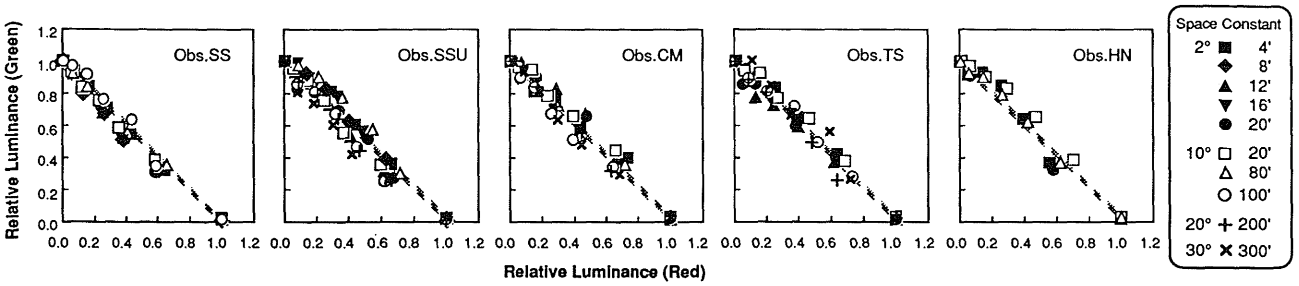

Fig. 3. Shading disappearance settings obtained for each space constant for each observer. Different symbols represent different space constants and/or stimulus sizes. The dashed line represents the prediction for the complete additivity.

sents the amount of red in the test color and the vertical axis represents the amount of green in the test color). Figure 2 shows each setting of the three tasks in a red and green color space for 20′ of 2° stimulus and 100′ of 10° stimulus of observer SS and SSU. The axes are scaled so that the luminance of the settings for each task for the pure red (horizontal axis) or the pure green (vertical axis) condition becomes 1.0. If the additivity law holds for a task, the data points should be aliened on a straight line with a slope of −1. Filled circles represent the settings for shading disappearance, open squares for minimum flicker, and open triangles for brightness matching. The error bars indicate ±1 standard error, which are shown when larger than the data point.

In Fig. 2, the data points for the shading disappearance settings and for the minimum flicker settings are closely plotted around the diagonal line of the additivity function for both conditions. On the other hand, the settings of brightness matching tend to be above the additivity function. Similar results were obtained for the other conditions and for the other observers.

Figure 3 shows the settings of shading disappearance for all conditions for each observer. The axes of each panel in Fig. 3 are the same as those of the panels in Fig. 2. Different symbols represent different conditions. The dashed line represents the additivity function.

It is shown that the shading disappearance settings fall close to the additivity function regardless of space constant or stimulus size (i.e. regardless of spatial frequency contents in the stimulus). This agrees with the conclusion of previous reports for the achromatic form pathway using different stimulus and/or tasks.[2,4] Figure 4 shows the setting of just appearance of shading for 80′ of 10° stimulus for observer SSU. Open triangles represent the setting of just appearance of shading for the reference color, open circles represent the setting of just appearance of shading for the test color, and open squares represent the setting of shading disappearance. The horizontal and the vertical axes are scaled so that the luminance of the settings for shading disappearance in the pure red or the pure green condition becomes 1.0. The additivity law of color mixture held for the setting of just appearance of shading for both condition as well as for the setting of shading disappearance.

These results suggest that the luminance or a luminance type additive mechanism is the achromatic intensity dimension for the mechanism that mediates the perception of shape from shading. The spatiotemporal characteristics of the stimulus figure do not affect the additivity law. This indicate that the difference between luminance and brightness cannot be attributed to the difference of spatiotemporal characteristics of the stimuli.

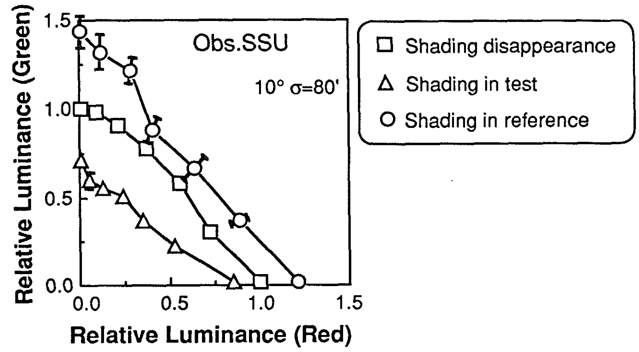

Fig. 4. Settings obtained for the 10° stimulus with 80′ space constant and the 10° stimulus with 100′ space constant for observer SSU. Open square represents the shading disappearance setting, open circle represents the setting of just appearance of shading in the reference field, and open triangle represents the setting of just appearance of shading in the test field. The axes are scaled so that the radiance of the red (the horizontal axis) or the green (the horizontal axis) became 1.0 when the red or the green is used alone for the shading disappearance setting. The error bars denote ±1 standard error.

Although the shading disappearance settings obeyed the additivity law regardless of space constant, their absolute values did not always agree across conditions. This contrasts with the fact that the absolute value of the minimum flicker was nearly constant across conditions. The change of the absolute settings for shading disappearance indicates that the relative sensitivity between the reference and the test changes depending on the spatial conditions. To evaluate the effect of space constant on the sensitivity, we calculated the ratio of the sensitivity for the shading disappearance to that for the minimum flicker. The ratio, S/F, does not include the influence of the macular pigment because the effect of the macular pigmentation should be the same as for the flicker and the shading settings. Figure 5 shows the S/F for the red and the green as a function of space constant. Filled symbols represent the S/F for the red and open symbols represent that for the green. Different symbols represent conditions of different stimulus conditions. The error bars indicate ±1

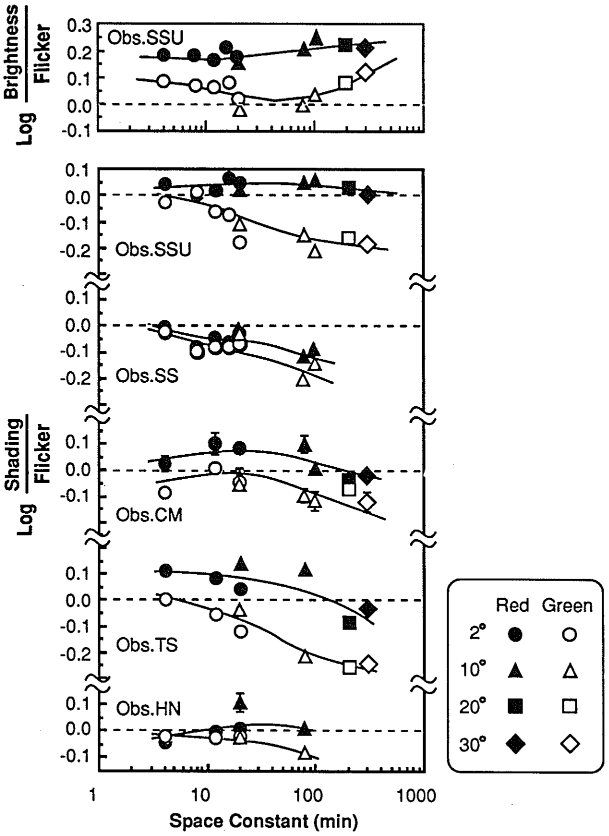

Fig. 5. The ratio of the shading disappearance setting to the minimum flicker setting as a function of space constant. Filled symbols represent the S/F for red, open symbols represent that for green. Different symbols represent different stimulus sizes. The error bars denote ±1 standard error (Lower panel). The ratio of the brightness matching to the minimum flicker setting as a function of space constant for observer SSU (Upper panel).

standard error. In addition, the ratio of the sensitivity for the brightness matching to that for the minimum flicker (B/F) are also plotted for observer SSU.

It is seen in Fig. 5 that the S/F for the green decreases with the increase of the space constant for all observers. The S/F for the red also tends to decrease with the space constant, although it is less systematic. This indicates that the shading disappearance setting is different from the minimum flicker setting at lower spatial frequency regions. This suggests that the luminance or the luminance-type additive mechanism that mediates the perception of shape from shading varies its spectral sensitivity dependently on the spatial frequency contents of the stimulus figure. Note that this change of S/F cannot be explained by the contribution of the brightness mechanism to the shading perception. If this were the case, the S/F would agree with the B/F. However, the space constant dependency of S/F for the green is very different from that of the B/F as shown in Fig. 5. The sensitivity change for the shading disappearance setting cannot be attributed to the contribution of the brightness mechanism.

One possible explanation of the dependency of spectral sensitivity on spatial frequency is the contribution of the short-wavelength-sensitive-cone (S-cone) at lower spatial frequencies. It is known that the upper limit on spatial sensitivity for S-cone is lower than that for the other types of cones.[5] This suggests that the sensitivity to the reference white becomes higher at lower spatial frequencies with little effect for the green and the red test colors. The relative sensitivity of green or red against white will decrease as the space contrast of the stimulus increases if this is the case.

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