Effect of Spatial Frequency on Chromatic Induction

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Introduction

Induction refers to the change of the color appearance of a light caused by the presence of neighboring lights. There are two major types of induction: color contrast, which occurs when the color appearance of a light shifts away from the color of the neighboring lights; and color assimilation, which occurs when the color appearance of a light shifts toward the color of the neighboring lights.

Previous studies reported that spatial properties are the main factor determining the transition from assimilation to contrast.[1-4] With high spatial frequency stimuli, assimilation occurs. With low spatial frequency stimuli contrast occurs. With intermediate spatial frequencies, variable effects are seen. The purpose of this study is to investigate the mechanisms of the induction. To achieve this goal we measured the induction effects for different stimulus spatial frequencies (0.8, 4.0, 6.0, and 9.0 cpd) to determine the transitional spatial frequency between assimilation and contrast. The use of a cone excitation space allows analysis of the spatial frequency effects on SWS and LWS/MWS cones chromatic pathways separately. A spread light model was developed to see whether optical factors might account for all or part of the assimilation effect.

Measure of the Induction Effects at Different Spatial Frequencies

In the experiment, induction effects for test stimuli of various spatial frequencies were measured by an asymmetric matching technique using a haploscope. The haploscope is a two-channel optical device in which an observer views the left half of a stimulus field with the left eye and the right half of the stimulus field with the right eye. Here the test stimulus was defined as the stimulus under the influence of the inducing stimulus. The match stimulus was the stimulus that was adjusted to the same appearance as the test stimulus. To measure the individual observers' null settings for the condition of the experiment, we used the minimum motion technique to set equiluminance of the three CRT phosphors for each observer.[5] Then, each observer's individual tritan line was determined with a modified minimally distinct border method. Each observer's L/M line was perpendicular to his/her tritan line.

Apparatus

A high resolution RGB monitor (Nanao, Flexscan T560i) was used to present the stimuli. The stimuli were generated by a Pixar II image processor controlled by a Sun 3 workstation. Luminances of the 3 phosphors were equated by using minimum motion photometric technique. Two surrounds were used: one is dark, the other is achromatic. The luminance was 12 cd/m^2 for the entire display.

Stimuli

The spatial configuration of the stimuli is shown in Figure 1. The stimuli consisted of two rectangular fields of 2° by 5.6°. In the test field, test stripes were flanked by inducing stripes. By means of the haploscope the match rectangular field was presented to the right eye and the test grating field was presented to the left eye. To make it easier for the observer to distinguish the test gratings from inducing gratings, the test bars are made slightly shorter than the inducing gratings. The ratio of the test stripe and inducing stripe is kept constant at 1:1. The spatial frequency of the test and inducing gratings vary from 0.8 cpd to 9.0 cpd session to session. Each observer wore spectacles with powers -1.0 diopter greater than the refractive corrections to ensure that the blue phosphor image could be focused on the retina.

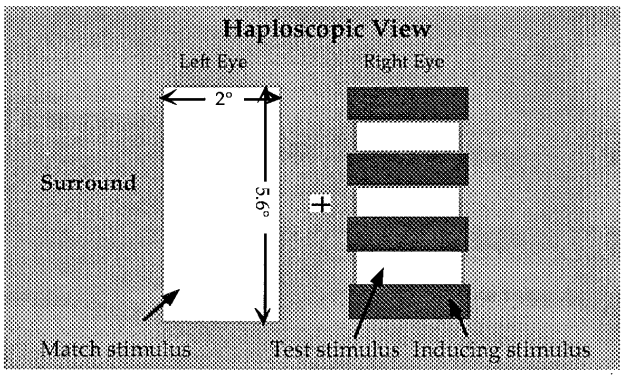

Figure 1. Spatial configuration of the stimuli used in chromatic induction experiment

The stimuli were specified in terms of the three cone excitations at equal luminance and are shown in Figure 2. One axis was the tritan axis, along which only SWS cone input varies, and the other was the L/M axis along which LWS and MWS cone inputs vary at constant SWS illuminance. In Figure 2, the solid squares represent the chromaticity coordinates of the three phosphors. The solid circles represent the nine inducing stimuli. The solid diamonds represent the ten test stimuli selected along tritan and L/M lines. The chromaticity coordinates are obtained by linear transformation of the Judd (1951) standard observer. The transformation equations used in the present study are shown in below.

$$\begin{aligned} L &= 0.15514\bar{x}' + 0.54312\bar{y}' - 0.03286\bar{z}' \\ M &= -0.15514\bar{x}' + 0.45684\bar{y}' + 0.03286\bar{z}' \\ S &= 1.0241\bar{z}' \end{aligned} \qquad (1)$$

where L, M, and S are the Smith-Pokorny (1975) cone fundamentals;[6] $\bar{x}'$, $\bar{y}'$, and $\bar{z}'$ are the Judd (1951) color matching functions; and $\bar{z}'$ is scaled so that the number of SWS cone trolands equals the number of the photopic troland for an equal energy spectrum. The cone trolands were defined as cone excitation weighted by the total retinal illumination as described previously.[7] Ten test colors were selected along two directions, a tritanopic confusion line and a L/M line. These lines intersected at equal energy white. There were nine inducing stimuli (inducers). The inducers on the same vertical line have the same LWS cone excitations (e.g., inducers 1 and 7).

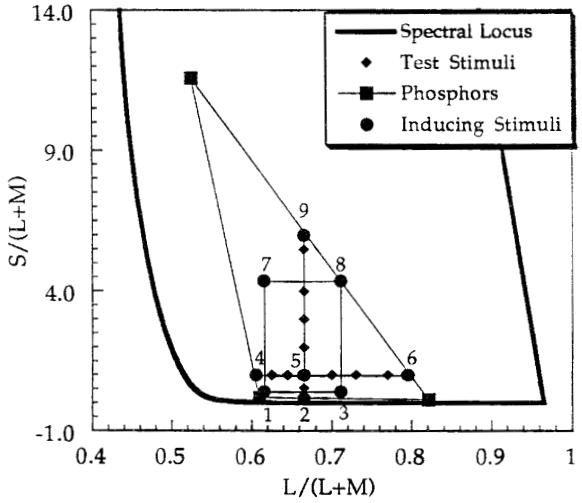

Figure 2. The coordinates of 3 phosphors, test stimuli and inducing stimuli selected for Judd (1951) observer

Methods

The method of asymmetric matching was used. The observer looked steadily at the fixation marks of central field for the observation period. The observer was instructed to match the colors in hue and saturation. A luminance adjustment was available to compensate for chromatic brightness differences. The observer made three matches for each stimulus color for a given inducing stimulus.

Observers

Four observers YZ, NW, CS and QJ with normal color vision took part in the experiments. Each observer had normal color vision as evaluated by the Ishihara Pseudoisochromatic Plates, Farnsworth-Munsell 100-Hue Test and the Rayleigh equation on the Neitz-OT anomaloscope.

Results

A subset of the data are shown in Figure 3. The spatial frequency decreases from the left to right. The top panels represent the data with a dark surround. The bottom panels represent the data with an achromatic surround. The data were described as vectors of chromatic change. The horizontal axis is LWS cone excitation, expressed as L/(L+M). The vertical axis is the SWS cone excitation, expressed as S/(L+M). The tails of the vectors represent the test stimuli. The arrowheads represent matches made with the inducing stimulus present. The filled circle in each of the graphs represents the chromaticity of inducing stimulus. All the graphs on each page are for the same inducer.

The data show that the chromatic changes of the test stimuli are in the direction toward the inducing stimulus with high spatial frequency stimuli (9.0 cpd, the left graphs in the figures) and away from the inducing stimulus with low spatial frequency stimuli (0.8 cpd, the right graphs in the figures). The data obtained at intermediate spatial frequencies (4.0 or 6.0 cpd) show that the chromatic changes of the test stimuli vary with inducing stimuli (the middle graphs in the figures).

A comparison of the left panel with the right panel shows that the presence of a surround changes the magnitude of contrast, but has little effect on assimilation. With low spatial frequency stimuli, the data show that the contrast effect is stronger with the dark surround than with the achromatic surround.

A Model of Spread Light

Method

To model spread light, it is supposed that each phosphor contributes a certain proportion of light from the inducer to the test stimuli, say a, b, and c for R, G, and B phosphors respectively. In turn, the same proportions of light from the test stimuli are contributed to the inducer. Let (R_I, G_I, B_I) and (R_T, G_T, B_T) represent the chromaticity coordinates of the inducer and the test stimuli in RGB space respectively, then the chromaticity coordinates of the model can be expressed as follows:

$$\begin{aligned} R_{model} &= (1-a) * R_T + a * R_I \\ G_{model} &= (1-b) * G_T + b * G_I \\ B_{model} &= (1-c) * B_T + c * B_I. \end{aligned} \qquad (2)$$

The values of a, b, and c were determined by minimizing the sum of the distances between each pair of model predictions and matches made by the observer for the 9 inducers and 10 test stimuli in cone space. The residual was the RMS of the square deviation between the match and the model.

Evaluation of the Model

To evaluate the spread light model, we calculated the amount of spread light coming from inducer into the test stimulus region by using a line-spread function derived by Westheimer[8]:

$$A(\alpha) = 0.47 \exp(-3.3\alpha^2) + 0.53 \exp(-0.93\alpha) \qquad (3)$$

where α is the distance from the line in minutes of arc. We computed the amount of light that spread into the test stimulus region by summing the $A(\alpha)$ produced from all lines in the inducing stimulus region to a horizontal line within the test stimulus region and the inducing stimulus region. For the calculation, all lines had a width of 0.05 minutes. The fraction of spread light from the inducing areas more than two cycles away from the test line was less than 0.03% for the highest spatial frequency stimulus (9.0 cpd) and was therefore not calculated in the results. The calculation was repeated for many horizontal lines in the inducing and the test area. The relative amounts of light for the stimuli with the spatial frequencies of 0.8 cpd and 9.0 cpd were computed across two cycles of the gratings. The amount of spread light on each line was normalized to that on the middle line of the inducing area. Therefore, the relative

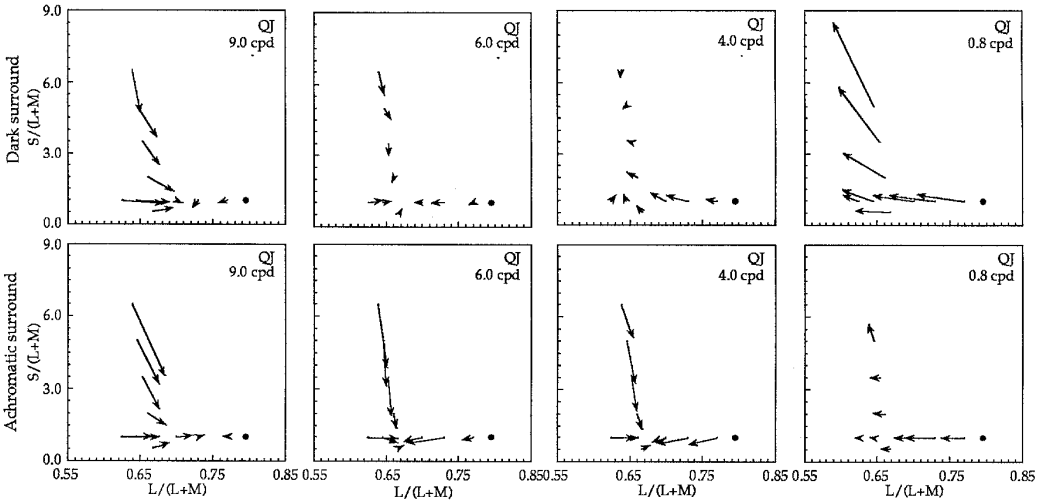

Figure 3. The induction data at different spatial frequencies for observer QJ. See text for further description

amount of light in the test region was equivalent to the fraction of light coming from the inducing region. The amount of spread light was least in the middle of the test stimulus region and increased towards the edge of the test stimulus region. For the stimulus with spatial frequency of 0.8 cpd, an insignificant amount of spread light reached the test stimulus region except in the area near the border of the inducing and test region. However, for the stimulus with spatial frequency of 9.0 cpd, the minimum fraction of spread light, which was on the middle line of the test stimulus region, was calculated as 16%.

For all of the observers, the fractions of the spread light predicted from the data are in the range derived from Westheimer's line-spread function. The model was able to fit the observers' data satisfactorily except Observer CS data which showed discrepancy in high SWS cone excitation region. The satisfactory fit of the model to most of the data and the amount of light spreading into the test region for the high spatial frequency (9.0 cpd) stimulus suggested that spread light model could be used to account for the assimilation effect.

Conclusions

This study explored the role of spatial frequency in chromatic induction. It was found that the spatial frequency of the stimulus was a major factor causing the transition from contrast to assimilation. Assimilation occurred at the highest spatial frequency used (9.0 cpd), whereas contrast occurred at the lowest spatial frequency used (0.8 cpd). At intermediate spatial frequencies (4.0-6.0 cpd) both contrast and assimilation could be observed depending on the inducer used.

The amount of the contrast also depended on the luminance level of the surround. The amount of the contrast with the achromatic surround (Y=9.5 tds) was smal-ler than the amount of the contrast with the dark surround.

This study's novel application of the cone excitation space to chromatic induction made it possible to investigate the mechanisms of chromatic induction in LWS/MWS cone and SWS cone chromatic channels separately. The spatial frequency at transition point from assimilation to contrast was in a range of about 2.5 to 7.0 cpd for both LWS/MWS cone and SWS cone pathways. The closeness of the spatial frequency at transition point for SWS cone pathway to the SWS cone acuity (about 6 cpd)[9] suggests that a relationship could exist between the SWS cone acuity and the transition from assimilation to contrast for the SWS cone channel.

The spread light model is able to fit most of the assimilation data. The fractions of spread light derived from the model for all the observers are in a theoretical range calculated from the line-spread function. Therefore, it can be concluded that spread light is a non-negligible causative factor for assimilation.

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