Sensitivity to Color Variations

Setareh Rafatirad, srafatir@uci.edu
CS 213, Prof. Aditi Majumder

Abstract

Investigating about a field consisting of numerous subfields would be insufficient if one only examines the subparts separately, because the intersections between them will be overlooked. Study of visual system is a good example in this respect. In a laboratory, we might be able to create a situation of having the impact of only one of the visual system subfields, but in the outside world, far from the artificial environment of the laboratories, we will observe the impact of all. Spatial vision and color vision are two subfields of visual system which we will be talking about them in this paper

1 Introduction

Visual perception of an object by human eye or other animals which have similar visual systems, includes information about both luminance and color variations. Given an object in shadow, will be perceived as having a small bluish color in a sunlit scene, presenting variations in both wavelength and luminance distributions (shadow itself represents luminance discontinuity). Although the variation in terms of wavelength distribution is trivial, the luminance variation is nontrivial (i.e., the intensity of the reflected light by the object drastically changes about 30 times depending on whether the object is illuminated directly or indirectly by a light-source), but even a small change in color gives additional information about the scene, thus color vision is more veridical.

Losing sensitivity to either of these subfields decreases the ability to perceive different scenes. In this paper we will discuss about the differences between sensitivity to color and luminance variations, mostly in human-like visual systems.

2 Chromaticity vs. Intensity

For animals like birds and insects which can find their food by color rather than luminance differences, having a visual system sensitive to color variations is very essential but not for ungulates and grass eaters which can easily distinguish their food from the surrounding environment. Fig 1 simply indicates this fact.

Fig 1a:Color image (more information)

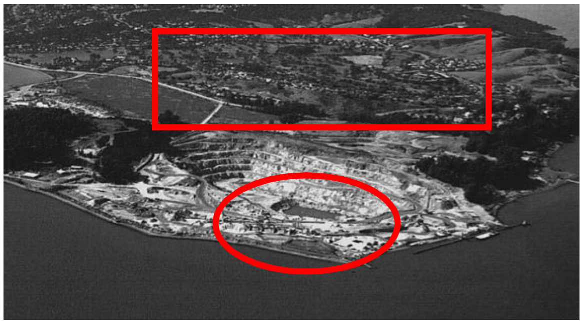

Fig 1b: losing information in the gray scale

Comparing the circle area with the square area in fig 1a, the first one is guessed to be a pool or some water container because of the bluish color, and the second one corresponds to a field covered by grass because of the greenish color. In fig 1b we lose this information and are not able to extract enough information from the scene to distinguish the two indicated areas.

In the next chapters we will explain about Color-mixture grating, Spatial and Temporal Contrast Sensitivity Functions for color and luminance, Color Contrast and Similitude, Minimally Distinct Borders, and presence of Multiple Color Spatial Frequency Channels in filtering behavior of the Color Contrast Sensitivity Function toward high spatial frequencies.

2.1 Color-mixture Grating

Summing different color gratings, we can create a color mixture grating. Depending on how we sum color gratings (Out-of-Phase/In-Phase), color-mixture grating will have different characteristics.

Out-of-Phase Summation

Given a red grating and a green grating (both isochromatic luminance gratings, i.e., both vary in terms of luminance not color and both gratings with identical luminance); summing 180˚ out-of-phase red grating with the green grating, the resulting color-mixture will be an isoluminant color varying grating. Fig 2a shows summing two out-of-phase isochromatic luminance gratings with identical luminance to get an isoluminant color grating. The sum of cone responses to the resultant red-green grating is shown in fig 2b in respect to luminance. Since the summation is of type *out-of-phase* and both component patterns have identical luminance, the sum of cone responses in respect to luminance is invariant. The difference in the cone responses (both cone types respond to both gratings with different amplitudes) to the same pattern in terms of chrominance is shown in fig 2c. Since the resulting pattern is a color varying pattern, the cone responses vary across the extent of the grating.

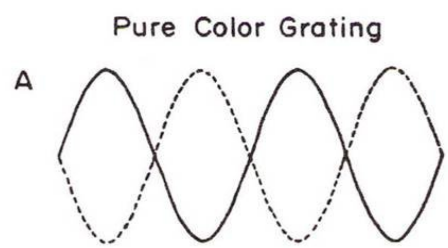

Fig 2a: Out-of-Phase summation

Fig 2b: Luminance Receptor sum

Fig 2c: Receptor differences

The corresponding isoluminant color-mixture grating in which the dominant wavelength is changing between two extremes red and green is shown in fig 3. Note that there are no variations in terms of color and luminance along the orthogonal axis but there is variation in terms of chromaticity across the width extent of the pattern.

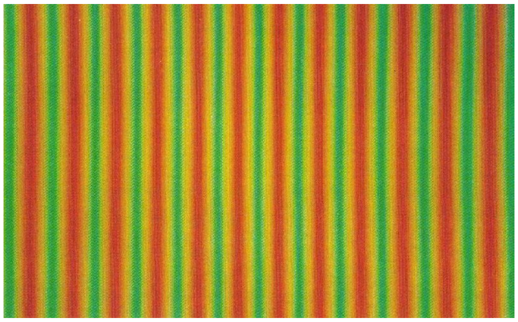

Fig 3 : Isoluminant Color mixture grating

In-Phase Summation

Given the same red grating and green grating, summing them in-phase, the resulting color-mixture will be an isochromatic luminance varying grating which is shown in fig 4a. The color which does not vary across the extent of the pattern is the intermediate color resulting from mixing two color components. Since we have summed the two component patterns in-phase, the amplitude of the luminance receptor sum varies from twice the mean to zero (fig 4b).

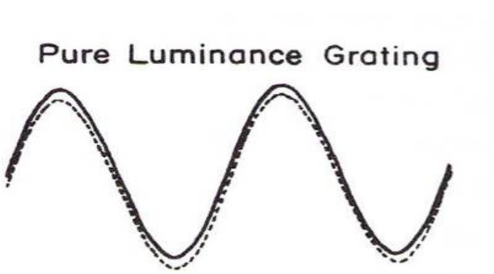

Fig 4a: In-Phase summation

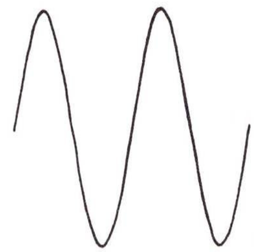

Fig 4b: Luminance Receptor sum

Fig 4c: Receptor differences

Finally the difference in the cone responses to the resultant grating in respect to chromaticity is shown in fig 4c. Since the pattern is isochromatic, no difference is obtained because there is only one color in the pattern.

There is an interesting phenomenon explained in the next section about how some the perception of color and luminance characteristics of an isoluminant color grating changes in different circumstances in human eye.

A Phenomenon

An isoluminant color pattern obtained by an out-of-phase summation sometimes has different characteristics in the human eye in different spatial frequencies. Van der Hoarst, de Weert, and Bouman (1967-1969) worked on pure color gratings and they noticed that an isoluminant red-green grating in low spatial frequencies has relatively constant luminance across its pattern and the dominant wavelength changes between two extremes(red and green), whereas in high spatial frequencies the grating is no longer perceived as an isoluminant color grating but rather looks like a monochromatic(color is the mixture of two extremes) luminance grating similar to the resultant grating that we explained in the in-phase summation section. There are some justifications for this phenomenon. Fig 5 shows this phenomenon (right side). Note that in high frequencies you observe the isoluminant red-green grating as a yellow-black grating luminance grating.

Van der Hoarst and Bouman reasoned that if we perceive the grating as a luminance varying patterns, it is probable that the grating was a luminance varying pattern which the human did not perceive it at the first place because of the low spatial frequency. But some studies show that there might be some optical factors to create luminance artifacts from an isoluminant color gratings. There are three optical factors in this regard which are likely to be the reason for generating the luminance artifacts; *axial chromatic aberration*, *diffraction by the pupil*, and *radial chromatic aberration*.

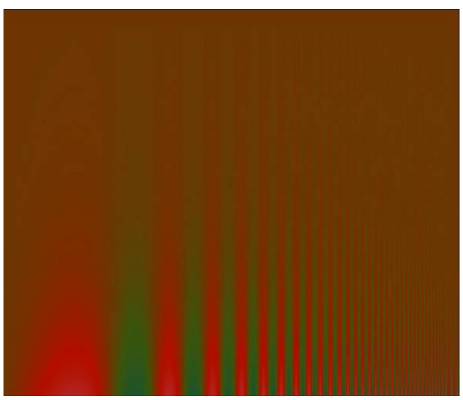

Fig 5: Isoluminant red-green grating changes in high frequencies to a yellow-black luminance grating

Axial chromatic aberration represents partial demodulation that is imaging lights of different wavelengths with different depths in the eye, so if a wavelength is in focus, the other one will be out of focus, therefore in case of having a sine wave, defocusing it will reduce its amplitude (neither its spatial frequency nor its phase). Axial chromatic aberration will produce a grating which varies in terms of color and luminance. Using a small artificial pupil with an achromatizing lens in front of the eye can virtually eliminate this effect.

Another optical factor which creates luminance artifacts is *diffraction by the pupil* which is increased by using the small artificial pupil. Finally, *radial chromatic aberration* represents the fact that lights of different wavelengths are differentially magnified at the retina producing beats (luminance artifacts).

There are some methods that can eliminate the luminance artifacts over a middle range of spatial frequencies but fail to eliminate them completely. In the following section we will explain the possible reason.

2.2 Spatial Contrast Sensitivity Functions (CSF)

According to some ample evidences [R.L. De Valois et. Al., Boynton, Hurvich], the visual system color analysis is based on three dimensions; luminance (black-white), red-green, and yellow-blue axes. We will explain and compare the behavior of their spatial contrast sensitivity function.

There are two important differences between Color and Luminance Contrast Sensitivity Functions [van der Hoarst et al. al. and Granger et al.]:
a) Sensitivity to pure color patterns in high spatial frequencies falls off earlier than sensitivity to luminance patterns. Human eye or animals with similar visual system

are less sensitive to color patterns in high spatial frequencies whereas they are more sensitive to luminance patterns in high spatial frequencies.

b) Color patterns have no or very little sensitivity attenuation towards low spatial frequencies i.e., they are low-pass filter whereas luminance patterns are not. Human eye is more sensitive to color patterns in low spatial frequencies than luminance patterns.

These differences are demonstrated in fig 6 for measuring a red-green grating spatial CSF with two criteria; pattern detection and hue detection. The sensitivity fall-off point is sooner with the hue detection than pattern detection criterion. However they look similar in terms of having a bow-shape structure. The triangular pattern shows the color pattern sensitivity and the circular pattern indicates the luminance pattern sensitivity.

Comparing red-green with yellow-blue grating spatial SCF, many reports [van der Hoarst et. al., Granger et al.] note that yellow-blue Spatial CSF is lesser sensitive to high spatial frequencies than red-green ,reasoned because of the sparse retinal distribution of S cones. However Mullen [2] reported no difference in behavior of these two dimensions in terms of high frequency cut-off points and reasoned the earlier results because of the effects of chromatic aberrations which we talked about earlier in this paper.

2.3 Temporal Contrast Sensitivity Functions (CSF)

Many experiments [Regan et al., D.H. Kelly] denote that there are similar differences as well as in section 2.2 between color and luminance Temporal CSFs. The sensitivity to color temporal CSF falls off sooner in high frequencies than luminance temporal CSF and color temporal CSF acts as a low-pass filter. This is demonstrated in fig 7.

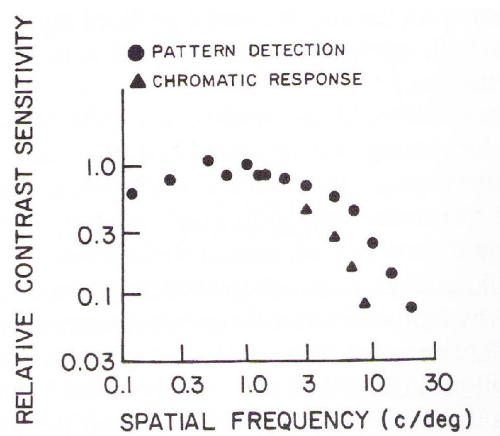

Fig 6: Color and luminance pattern Sensitivity for red-green dimension in different spatial frequencies. The color pattern is less sensitive towards high spatial frequencies, thus the fall-off point is lower than the correspondent luminance pattern.

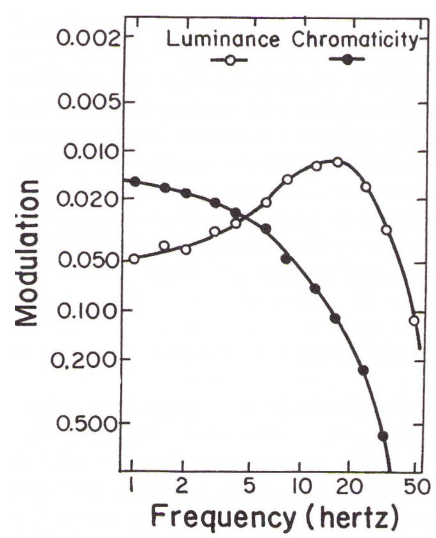

Fig 7: Color and luminance temporal CSFs.

2.4 Color Contrast and Similitude

Contrast and similitude are two opponent concepts in pattern detection which are used in different frequency levels. As mentioned earlier in this paper, sensitivity to luminance patterns is more at mid and high frequencies and less to low frequencies and sensitivity to color patterns is more in low frequencies and less to high frequencies. These statements state that in case of having a color pattern, we can use *Contrast* to detect the pattern at low frequencies while we won't be able to detect color patterns by using *Contrast* at high or even mid frequencies. This is inversely true for luminance patterns. In both cases, when the eye is incapable of detecting the pattern with use of *Contrast*, it will use *Similitude* which is defined as the similarity of the pattern to its background rather than being different from the background. Table 1 denotes that when we use Contrast/ Similitude.

Patterns	Low Spatial frequencies	Mid Spatial frequencies	High Spatial frequencies	Very high Spatial frequencies
Luminance patterns	_	Contrast	Contrast	Similitude
Color patterns	Contrast	Similitude	_	_

Table 1: Contrast vs. Similitude

The use of *Contrast* and *Similitude* is shown in fig 8 and fig 9.

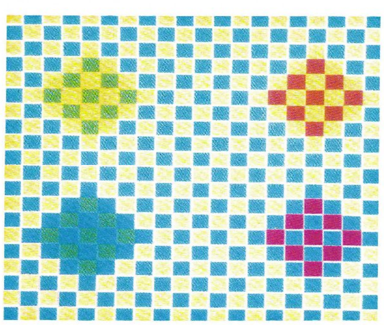

Fig 8: Similitude

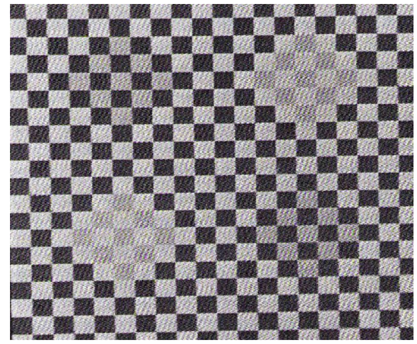

Fig 9: Contrast

Fig 8 is presenting a pattern in mid frequency and the same pattern in gray-scale in presented in fig 9 at the same frequency level. On the right side of fig 8, two patterns are demonstrated which are perceived differentially. On the top right corner, there is a red pattern on a yellow background and bellow that, there is a purple pattern on a blue background but the fact is that both of these patterns are the same red but with different perceptions. According to Table1, in mid frequencies the eye is less sensitive color patterns, thus it uses Similitude in place of Contrast to detect the pattern, so the red pattern on a yellow background is perceived to be more similar to yellow and the same red on the blue background is perceived to be more similar to blue(purple). The same explanation is true for the left side patterns in fig 8.

Now consider fig 9. Fig 9 is the gray-scale of fig 8 which gives the luminance pattern. In this pattern which is again in the mid frequency level, the eye is sensitive enough to detect the pattern so it uses *Contrast*. On the top right corner we have the same gray as well as at the bottom right corner but because we are using *Contrast* to detect the pattern, the gray with the black background is perceived to be lighter than the same gray on the white background.

In color interactions, color similitude very essential while color contrast is relatively rare.

3 Significance of color CSFs for vision

Earlier in section 2, we highlighted the significant role of color to extract details from a visual scene; also we described the limitations of color CSF vs. luminance CSF in high frequencies. Borders and edges occur in high spatial frequencies in which there is a significant change. We know that human eye is not sensitive to color patterns in high frequencies; therefore we use luminance patterns because the eye is more sensitive to luminance patterns in high frequencies and is able to distinguish the edges.

We will first address which patterns are better for object identification briefly in section 3.1 and then will investigate if color CSF reflects the filter characteristics of single or multiple channels, based on some psychological evidences in section 3.2.

3.1 Minimally distinct borders

The first task in object identification is border distinction or edge detection. Boynton examined the role of luminance and color differences in object identification and came up with the following results:

- Isoluminant color patterns give minimal distinction in terms of identifying borders.
- Isochromatic luminance patterns or any other pattern which has luminance variations give sharper border and better object detection.

3.2 Multiple color Spatial Frequency Channels

There are some psychological evidences reasoning the limitations of color CSF towards high frequencies because of the filter characteristics of multiple channels. One group of evidence came from *Selective Adaptation Studies* [Blakemore et. al., Devalois et. al.]. It is reported that adaptation to an isoluminant color grating (e.g. red-green), reduces the sensitivity to another isoluminant color grating with the same color (i.e. red-green) and similar spatial frequency. Similar to luminance gratings, the sensitivity reduction in the color CSF is band limited whereas it is broader in bandwidth than comparable luminance CSFs.

Another group of evidence applies to *Masking Studies* [Devalois et. al.]. The experiment is done by superimposing an isoluminant color grating (e.g. red-green) on another isoluminant color grating of the same colors (i.e., red-green) with identical luminance and same or different spatial frequency. This has the same results as equivalent functions obtained from luminance gratings [Pantle, Foley et. al.] but it is broader (Fig 10) similar to the result from *Selective Adaptation Studies*. This experiment is the color-color masking which has a test color grating superimposed by a mask color grating (visual masking).

Fig 10 shows that both luminance-luminance and color-color masking [3] functions are band-pass and centered on the test frequency but color-color masking is broader in bandwidth than luminance functions.

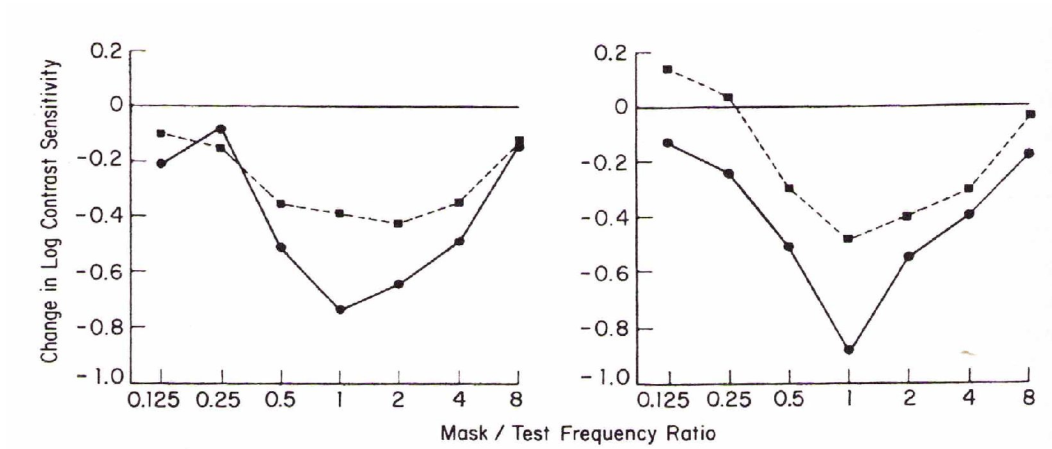

Fig 10: Masking effect for isoluminant color-color gratings (dashed-line) and isochromatic luminance-luminance gratings (solid-lines).

We talked about color-color and luminance-luminance gratings; now let's have a look at cross-masking effects when the masking function is a pure color grating which is superimposed on a luminance grating test and vice versa.

In a color mask-luminance test condition:

- It is more profound than having a luminance mask-luminance test condition.
- It is as effectively as applying a luminance test to a luminance mask, thus there would no loss (high sensitivity).

In a luminance mask-color test condition:

- It is less profound than applying color mask on luminance test.
- When mask and test are of the same frequency, there would be a significant loss in sensitivity.

This confirms what we stressed though out the paper that although luminance CSF is good in identifying contours and giving the overall shape, but the significance of color should not be underestimated.

4 Conclusion

To find out about a field, other than investigating its subfields separately, the intersections between them also should be considered and nothing should be underestimated. Throughout this paper we scratched many experiments in both color vision and spatial vision territory and concluded interesting points; the main point is that based on different needs we will require both these fields to have a more complete understanding of the outside world.

5 References

[1] Spatial Vision, *Russell L. De Velois, Karen K. De Valois*

[2] The Contrast Sensitivity of human Color Vision to red-green and blue-yellow chromatic gratings. *Kathy T. Mullen, 1985, Cambridge CB2 3EG*

[3] Spatial Vision (Course Slides), *Prof. Aditi Majumder*

frequency is lower because there are more frequency sensitive cells.

Sensitivity to Color Phase

At low spatial frequencies we can distinguish different colors. At high spatial frequencies we only perceive a mixture of colors because we don't have spatial phase information in high frequencies so we can not determine which part is which color.

5 Conclusion

In this paper we learned that the human visual system can localize patterns in two different ways: one-to-one retinotopic mapping and phase information from some special cells. We also learned that we are sensitive to the spatial phase in some degree although we are almost insensitive to absolute phase and our detection is more position dependent rather than phase dependent in high spatial frequencies. At the end we learned a little bit about the physiology of the visual system and different cells involved in this process.

6 References

[1] Spatial Vision, *Russell L. De Velois, Karen K. De Valois*