THE VISUAL PERCEPTION SENSITIVITY FOR ACHROMATIC NOISE AND CHROMATIC NOISE

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ABSTRACT

We often need to consider the influence on human perception when we develop an image processing algorithm or design parameters for image processing. The perception of color noise is also important for understanding the human vision system (HVS). Although we can use the CSF to express the property of achromatic noise appearance, it is not so easy to be applied to colors. While the CSF can be explained by a primary color vision, a color appearance is governed by higher order mechanisms. In this paper, we show the quantitative difference between achromatic and chromatic noise appearance. To reveal the perception of color noise quantitatively, we have conducted subjective experiments with modeled achromatic and chromatic noises using the 2AFC method. According to the results, it is shown that the ratio of luminance noise sensitivity to color noise sensitivity is 10^0-10^2 depends on their spatial frequencies and background colors.

Index Terms—*Visual system, Noise measurement, Color measurement, Noise generators, Image processing*

1. INTRODUCTION

When we develop an image processing algorithm or design parameters for image processing, we often need to consider the influence it has on human perception. Although the denoising process [1, 2] is often used to improve the quality of images recently, there are few metrics expressing the perception properties for noise. It might be caused by a shortage of the knowledge of the human perception properties. We are aiming to design a metric for color noise by inspecting the property of noise perception. In our previous study [15, 16, 17], we studied the dependence of perceived color noise on the direction of color noise and surrounding colors. In this paper, we study the sensitivity properties of color noise perception by conducting a subjective experiment. The sensitivity depends on noise model, spatial frequency, background color, LCD luminance level and individuals.

The contrast sensitivity function (CSF) is used as the HVS response in some image processing or metrics such as in S-CIELAB [3]. The CSF of color is usually measured through perceptual experiments using various frequency stripes with opponent colors [7, 12]. Although the chromatic CSF [7] works as a low-pass filter that the color signals are more visible at lower spatial frequency, the luminance CSF works as a band-pass filter. There is a theory that the contrast sensitivity is determined by the internal noise in the human vision system [12]. Color noise property contains background color element and noise property (achromatic noise or chromatic noise). It is uncertain which CSF property (achromatic or chromatic) can explain the perception properties about color noise.

Color image processing with the HVS starts in the eye. Light that entered into the eye is influenced by the aberration of the ophthalmus [8], and is captured by the LMS cones on the retina. The ganglion cells on the retina, neurons in a lateral geniculate nucleus (LGN) and neurons in V1 process vision signal [6, 13, 22]. Several color vision models treat the LMS signals [18], i.e. opponent model, two-stage model [11] and multistage model [14]. In addition, color and luminance signals are processed different pathway [21].

The noise masking property has been studied for understanding color perception of HVS. According to Hansen et al. [4], perceived noise is largely masked when signal and noise are modulated along the same direction in the opponent color space. The cardinal mechanism [5] is the popular color perception model, but this model cannot explain properties about noise masking [6].

Song et al. [9] performed perceptual experiments to examine the dependency of color noise on directionality, luminance and frequency, using vector noise moderated by an octave filter. Lucassen et al [10] measured the JNDs of color noise about lightness, chroma and hue, with the experiments about two chromatic and one lightness noise directions at background colors.

2. DEFINITIONS

2.1. Noise Model

The noise model is additive noise to image or patch defined as:

$$\mathbf{G}(x, y) = \mathbf{I}(x, y) + \mathbf{n}(x, y)\,, \tag{1}$$

where $\mathbf{I}(x,\ y)$ represents color at position $(x,\ y)$, and $\mathbf{n}(x,\ y)$ represents the additive color noise defined by the noise model. We use CIELAB color space, $\mathbf{I}(x,\ y)$, $\mathbf{n}(x,\ y)$ and $\mathbf{G}(x,\ y)$ are represented by (L_c, a_c, b_c) , (n_L, n_a, n_b) and (L_n, a_n, b_n) respectively. We define two noise models, the color noise model and luminance noise model. The color noise model generates equiluminant chromatic noise,

$$(L_n, a_n, b_n)_{\mathrm{Color}} = (L_c, a_c + n_a, b_c + n_b), \tag{2}$$

where $\mathrm{n_a}$ and $\mathrm{n_b}$ represent Gaussian noise. The luminance noise model generates achromatic noise,

$$(L_n, a_n, b_n)_{\mathrm{Lum}} = (L_c + n_L, a_c, b_c), \tag{3}$$

where n_L represents Gaussian noise.

2.2. Noise Sensitivity and Threshold

The noise sensitivity (s_n) is the inverse of the perception threshold (t_n) of noise:

$$s_n = {t_n}^{-1}. \quad (4)$$

When the noise level decreased, the appearance of the noise becomes blared, ambiguous and invisible. The threshold level means the fifty percent of probability that the noise is visible.

3. EXPERIMENT

We conducted the perceptual experiments of noise to confirm the effect to the visual perception between noise models, spatial frequencies, background colors, LCD luminance levels and individuals. We used the two alternative forced choice (2AFC) experiments to obtain the noise sensitivity. Subjects replied whether they could see the displayed noise or not. Fig. 1 illustrates our experiment. We displayed two color patches simultaneously on a LCD monitor. One color patch includes additive noise and another is a color patch without noise. Subjects could confirm the existence of noise by comparing these patches. We used two noise models, luminance noise and color noise, previously described. Seven background colors are described in Table 1. A session of the experiment was conducted with a specific spatial frequency. We use seven different spatial frequencies (13, 6.5, 3.2, 1.6, 0.81, 0.40, 0.20 [cycle/degree (cpd)]). Table 2 summarizes these conditions. The experiments were conducted with taking into account the chromatic adaptation effect and after-image. The color of patches was randomly changed after each judgment. Three subjects (MS, RS and MN), a male and two females, 30's, with normal color vision participated in the experiments. RS and MS had corrected visual acuities by glasses to have 20/20 and 20/25 vision respectively, while MN had 20/10 vision with naked eye. Additionally we conducted the experiment with two monitor luminance settings, 80[cd/m^2] and 200[cd/m^2].

We used EIZO CG-241W (the pitch size is 0.27[mm/pix]) as the calibrated monitor to sRGB color space. The observation distance was 40cm. The various spatial frequencies of noise were generated by enlarging the noise by the iterative bilinear (IB) method and nearest neighbor (NN) methods. The magnification ratio was power of two, from 1 to 64 times.

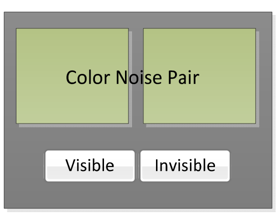

Fig. 1 The measurement of color noise perception.

4. EXPERIMENT RESULTS

4.1. Measurement of Noise Threshold

We analyzed the results of the experiments and decided the noise perception threshold. To obtain the perception threshold (t_n), we used the sigmoid function as the regression function. The sigmoid function shows the probability of visible judgments (p_{vis}) against a noise level (σ_n). The sigmoid function is expressed by:

$$p_{vis} = \frac{1}{1+\exp(-c\cdot(\sigma_n - t_n))}. \quad (5)$$

where c is constant value depends on the experiment.

Table 1 Background color of patch

Color	a*	b*	Color	a*	b*
Gray	0.0	0.0	Purple	64.8	-10.1
Red	66.0	52.1	Yellow	-0.1	46.1
Green	-45.1	42.9	Blue-violet	64.9	-60.1
Blue	30.1	-68.0			

Table 2 Conditions of experiments

ID	Type	Num	Value
(a)	Noise Model	2	Luminance and color
(b)	Spatial Frequency	7	13, 6.5, 3.2, 1.6, 0.81, 0.40, 0.20 [cpd]
(c)	Color	7	Ref. Table 1
(d)	LCD luminance	2(1)	80 and 200 [cd/m^2] (*1)
(e)	Resize Methods	2(1)	Iterative Bilinear (IB) and Nearest Neighbor (NN)(*2)
(f)	Subjects	3	MS, RS and MN
	Total conditions	588	$=2_{(a)}*7_{(b)}*7_{(c)}*$ (*3)

(*1) 200[cd] condition is conducted by one subject (MS).
(*2) MN participates in our nearest neighbor experiments.
(*3) $\{(2_{(80cd)}+1_{(200cd)})_{\text{Iterative Bilinear}} + (3_{(80cd)}+1_{(200cd)})_{\text{Nearest Neighbor}}\}$

4.2. Noise Sensitivity Properties

The luminance noise sensitivities of MS and RS are shown in Fig. 2 and Fig. 3 respectively. The sensitivity shows band pass property as with gray CSF property. It is highest at 1.6~6.5 [cpd] when gray and yellow background colors. The properties of other background colors show weaker band pass property. The regression functions of the sensitivities (s_n) are expressed by:

$$s_n = 10\hat{}\left(-(a_1 \cdot (log_{10}(f_s))^2 + a_2 \cdot log_{10}(f_s) + a_3)\right), \quad (6)$$

where f_s is a spatial frequency. a_1, a_2 and a_3 are parameters, these value are 1.16, -1.06 and -0.70 respectively when gray background color. We use the equation (6) as a regression function in all experiment conditions. Fig. 4 shows the sensitivity of the luminance noise resized by NN. The most sensitive spatial frequency in Fig. 4 (NN) is lower than Fig. 2 (IB). Although this relationship is similar to the relationship between the sine wave CSF and the square wave CSF [23], there is no peak shift in CSF. Fig. 5 shows the sensitivity of the luminance noise at the 200 [cd/m^2] LCD condition by MS. Although we expected the sensitivity at 200[cd/m^2] would be higher than 80[cd/m^2] as with CSF [12], it was similar to 80[cd/m^2] results except the higher peak.

Fig. 6, Fig. 7 and Fig. 8 show the color noise sensitivities. Although the sensitivity for NN noise (Fig. 8) decreased almost monotonically when the spatial frequency of noise increased, the noise sensitivities for IB noise (Fig. 6 and Fig. 7) have little dependency on spatial frequency.

We show the subjects dependency in Table 3. The values are averaged between background colors. There is large subjects' dependency especially in luminance noise.

5. DISCUSSION

5.1. Noise Sensitivity

Although the color difference in CIELAB is often used in image processing, we sometimes encounter a problem when the impacts of chromatic difference and achromatic difference to the human perception are different. The sensitivity level for color noise is less than one for luminance noise. According to Fig. 2 and Fig. 6, when we compare the noise perception thresholds between luminance noise and color noise, the noise sensitivity of luminance noise varies 1-200 times depending on the background color. Fig. 9 indicates the ratio between color noise sensitivity and luminance noise sensitivity measured by subjects (resized by IB conditions). These numerical differences reflect both the property of CIELAB color space and the property of perception sensitivity.

Fig. 10 (black points and a line) shows the sensitivity comparison of the luminance NN noise between RS (s_{lnRS}) and MS (s_{lnMS}). The regression function in Fig. 10 (black) is:

$$\log(s_{lnRS}) = 2.0\log(s_{lnMS}) - 0.31. \tag{7}$$

This equation means the luminance noise sensitivity of RS is two times more sensitive with log scale than one of MS. However, this obvious difference between two subjects was not shown in the results of IB noise. Fig. 10 (red points and a line) shows the sensitivity comparison of the color noise between RS (s_{cnRS}) and MS (s_{cnMS}). The regression function in Fig. 10 (red) is:

$$\log(s_{cnRS}) = 0.84\log(s_{cnMS}) - 0.14. \tag{8}$$

As compared with the luminance noise sensitivity, the color noise sensitivity has little individual difference.

Table 3 The relationship of the sensitivity thresholds and subjects at 0.2[cycle/deg], resized by NN condition.

Subjects	Thresholds		Lum:Color Ratio
	LumNoise	ColorNoise	
MS	0.16	1.08	6.70
RS	0.03	1.19	39.24
MN	0.02	0.66	34.44
MS(200[cd/m2])	0.22	1.29	5.84

5.2. Comparison to Previous Results

We had conducted the detail experiments specialized in the color noise [17]. The order of sensitivities to the background color is similar to color noise results (Fig. 6, Fig. 7 and Fig. 8). The most sensitive background color is blue-violet and the least is green.

The experiment method in this paper is the 2AFC method, the previous experiments [15, 17] was the compare method. The compare method compares a base noise to a target noise. It is difficult to compare luminance noise and color noise or to compare noises with different spatial frequencies. The measurement by 2AFC method is conducted at a sensitive condition near the just noticeable difference (JND). Subjects need to train to judge steadily. Therefore, we need many hours to measure.

5.3. Human Vision System

Although the sensitivity for luminance noise with gray or yellow background color shows band pass property similar to the achromatic CSF [7], the luminance noise sensitivity with other background color shows low pass property similar to the chromatic CSF. These characteristics could indicate color processing in the human brain. This insensitivity at low spatial frequency of band pass property can be accounted for by a lateral inhibition in the neural system [12]. A lateral inhibition or a band-pass property can be expressed by the activity of a type I opponent cell or double-opponent cell [13]. The band pass property in the luminance noise sensitivity would be caused by the activity of a double-opponent cell. Considering the subject dependency, although the visual sensitivity of RS was better than MS in the luminance noise results (Fig. 10), the results of color noise were similar. In this regard, there are several causes are conceivable. The first possible cause is the optics property of eye, including the visual acuity or the effect of chromatic aberration [19]. The second possible cause is the sensitivity itself of the L or M cone on the retina. The other possible cause is the difference of the L:M cone ratio [20].

5.4. Perceived Color Noise Model

In the previous paper [16, 17], we had defined the perceived color noise level P_N by:

$$P_N(\mathbf{I},\mathbf{G}) = \max\left(\frac{|\cos(\phi)|}{k_{LC}} \frac{\sigma_{CP}(\theta,a_c,b_c)}{\sigma_V} \frac{\sigma_{LP}(L_c)}{\sigma_{ab}} dC, dL\right), \tag{10}$$

where k_{LC} is the perceptual sensitivity ratio of achromatic noise to chromatic noise. The results of this paper can be applied to k_{LC}. According to Fig. 9, k_{LC} should be 1-200 depends on the background color (a_c, b_c), spatial frequency and subjects. The confirmation of this equation is our future task.

6. CONCLUSIONS

In this paper, we conducted the 2AFC experiments about the basic human perception property of noise. We measured the sensitivities of luminance noise and color noise, resize methods, background color, spatial frequency, and LCD luminance. We showed the perception difference quantitatively between luminance noise and color noise in the CIELAB color space. The perception of luminance noise is 1-200 times more sensitive than the one of color noise, depends on the background color, spatial frequency and subjects. Although the luminance noise sensitivities with gray or yellow background color showed similar properties to achromatic CSF, the luminance noise sensitivities with other background color did not show the clear peak unlike achromatic CSF. Our results show the basic human properties. This will be useful to develop an image-processing algorithm and to design parameters. We will examine more subjects and build/test the image quality model.

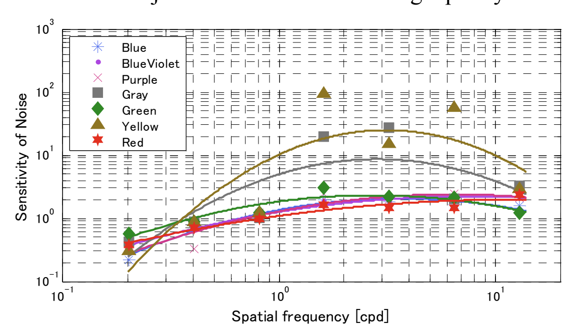

Fig. 2 The noise sensitivities of luminance noise, dependence on spatial frequency and background colors. Solid lines are regression curves and markers are experiment results. (MS, 80[cd/m²], IB).

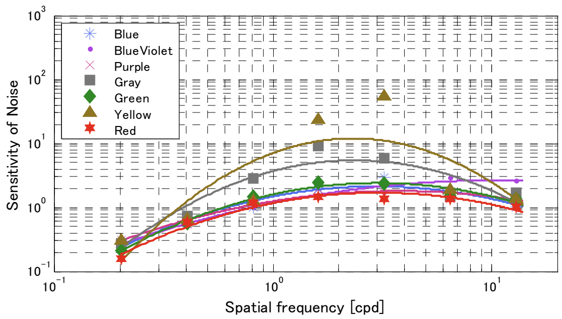

Fig. 3 The noise sensitivities of luminance noise (RS, 80[cd/m^2], IB). The annotation is same as Fig. 2.

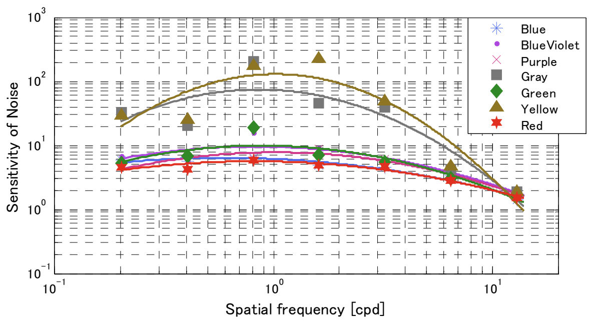

Fig. 4 The noise sensitivities of luminance noise (MS, 80[cd/m^2], NN).

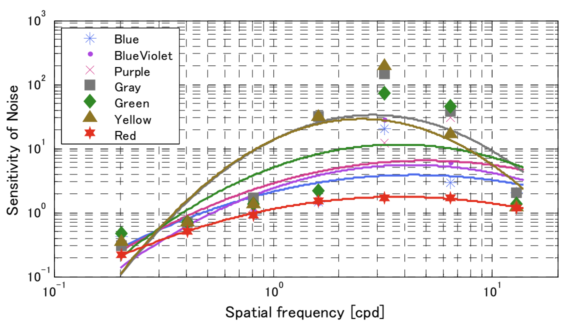

Fig. 5 The noise sensitivities of luminance noise (MS, 200[cd/m^2], IB).

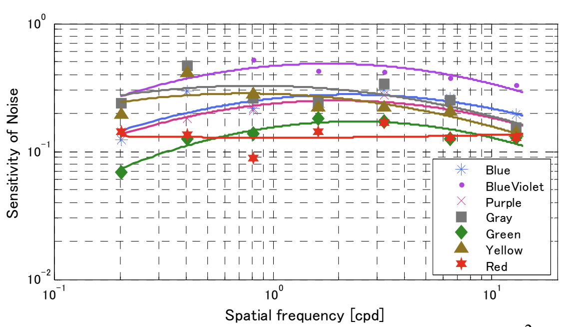

Fig. 6 The noise sensitivities of color noise (MS, 80[cd/m^2], IB).

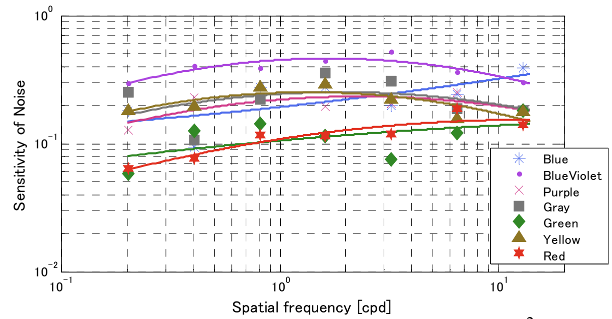

Fig. 7 The noise sensitivities of color noise (RS, 80[cd/m^2], IB).

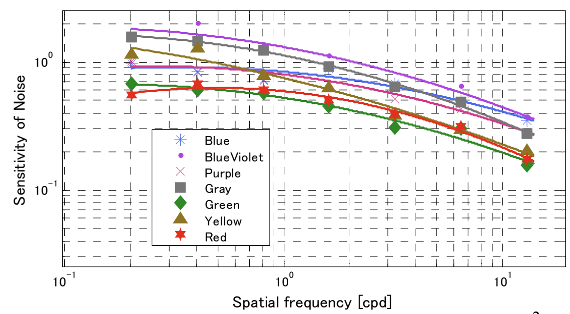

Fig. 8 The noise sensitivities of color noise (MS, 80[cd/m^2], NN).

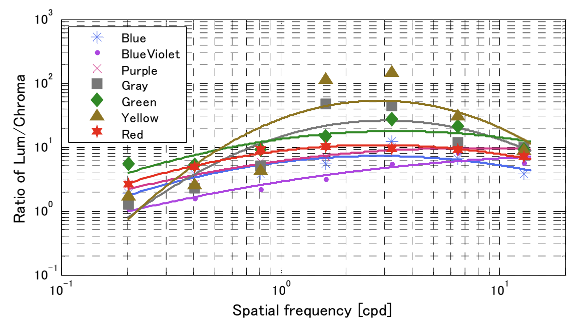

Fig. 9 The ratio of luminance noise sensitivity to color noise sensitivity. The ratio has root in the results about IB noise, in average between subjects.

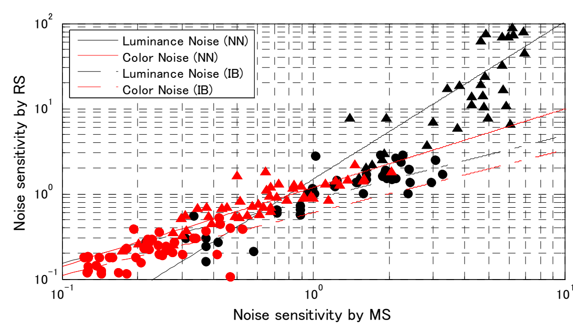

Fig. 10 The comparison of sensitivity between subjects, RS and MS at 80[cd/m^2]. The black points and lines show the results of luminance noise experiments. The red ones show for color noise. Triangle points represent the sensitivities of NN noise, and dots represent the sensitivities of IB noise.

7. REFERENCES

[1] C. Tomasi and R. Manduchi, "Bilateral Filtering for Gray and Color Images", *IEEE International Conference on Computer Vision (ICCV)*, pp. 839-846, 1998.

[2] K. Huang, Z. Wu, G. S. K. Fung, "Color Image Denoising with Wavelet Thresholding based on Human Visual System Model", *Signal Processing: Image Communication,* vol. 20 (2), pp. 115-127, 2005.

[3] X. Zhang and B. A. Wandell, "A spatial extension of CIELAB for digital color image reproduction", *SID Journal,* vol.5(1), pp.61–63, 1997.

[4] T. Hansen and K. R. Gegenfurtner, "Higher level chromatic mechanisms for image segmentation", *Journal of Vision*, vol.6, pp.239–259., 2006.

[5] J. Krauskopf, D. R. Williams and D. W. Heeley, "Cardinal directions of color space", *Vision Research,* vol.22. pp.1123-1131. 1982.

[6] R. T. Eskew, "Higher order color mechanisms: A critical review", *Vision Research*, vol.49, pp.2686-2704, 2009.

[7] K. T. Mullen, "The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings.", *The Journal of Physiology*, vol.359, pp.381-400, 1985.

[8] A. B. Poirson and B. A. Wandell, "Appearance of colored patterns: pattern-color separability", *J. Opt. Soc. Am. A*, 10, 2458-2470, 1993.

[9] X. Song, G. M. Johnson and M. D. Fairchild, "Minimizing the Perception of Chromatic Noise in Digital Images", *IS&T/SID 12th Color Imaging Conference*, Scottsdale, 2004.

[10] M.P.Lucassen, P.Bijl and J.Roelofsen, "The perception of static colored noise: detection and masking described by CIE94", *Color Research and Application*, vol.33(3), pp.178-191, 2008.

[11] J. C. R. Ingling and B. H. P. Tsou. "Orthogonal combination of the three visual channels", *Vision Research*, vol.17(9), pp.1075–1082, 1977.

[12] P. G. J. Barten, "Contrast Sensitivity of the Human Eye and its Effects on Image Quality", *SPIE Press*, 1999.

[13] S.G.Solomon and P.Lennie, "The machinery of colour vision", *Nature Reviews Neuroscience*, vol. 8, pp. 276-286, 2007

[14] R. L. D. Valois and K. K. D. Valois. "A multi-stage color model", *Vision Research*, vol.33(8):1053–1065, 1993.

[15] M. Shohara and K. Kotani, "Measurement of Color Noise Perception", *IEEE International Conference on Image Processing (ICIP) 2010*, pp. 3225-3238, 2010.

[16] M. Shohara and K. Kotani, "The Dependence of Visual Noise Perception on Background Color and Luminance", *28th Picture Coding Symposium*, 2010.

[17] Makoto Shohara and Kazunori Kotani, "Modeling and application of color noise perception dependent on background color and spatial frequency", *IEEE International Conference on Image Processing (ICIP) 2011*, pp.1689-1692, 2011

[18] R. Shapley and M. Hawken, "Color in the Cortex single- and double-opponent cells", *Vision Research*, vol. 51(7), pp.701-717, 2011

[19] D.H.Marimont and B.A.Wandell, "Matching color images: the effects of axial chromatic aberration", *J. Opt. Soc. Am. A*, vol.11-12, pp. 3113-3122, 1994.

[20] M.V. Danilova, C.H. Chan, J.D. Mollon, "Can spatial resolution reveal individual differences in the L:M cone ratio?", *Vision Research*, vol. 78(15), pp. 26–38, 2013.

[21] K. T. Mullen and M. A. Losada, "Evidence for separate pathways for color and luminance detection mechanisms", *JOSA A*, vol. 11(12), pp. 3136-3151, 1994

[22] B. R. Conway and M. S. Livingstone, "Spatial and Temporal Properties of Cone Signals in Alert Macaque Primary Visual Cortex", *The Journal of Neuroscience*, vol.26(42), pp.10826-10846, 2006

[23] F. W. Campbell and J. G. Robson, "Application of Fourier analysis to the visibility of gratings", *J.Physiol.*,197(3), pp.551-566, 1968.