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Color Discrimination Experiments using Metameric ipRGC Stimuli

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Abstract

In order to investigate the effect of ipRGC on color discrimination, it is necessary to reproduce two metameric light stimuli (we call these stimuli as metameric ipRGC stimuli) that have the same amount of cones and rods but different stimulus amount of ipRGC. However, it is difficult to independently control the amount of only ipRGC stimulation because the spectral sensitivity functions of the cones and rod overlap that of ipRGC in the wavelength band. So far, researchers have not addressed a comprehensive analysis of metameric ipRGC stimuli and color perception experiments for those stimuli. In this study, first, we proposed the calculation method of metameric ipRGC stimulus based on the orthogonal basis functions of human photoreceptors. Then, we clarified the controllable range of metameric ipRGC stimulus in the color gamut. Second, we conducted subjective evaluation experiments for investigating the discriminative colors due to metameric ipRGC stimuli. We showed the effects of ipRGC on color discrimination.

Introduction

Investigations of color perception and discriminations are fundamental work in the research filed of color science. Several types of research suggested that the spectral sensitivities of L, M, S cones and rods were optimized for the natural environment and natural scene statistics [1-4]. Actually, we perceived colors through the cones and rods inputs and the human visual system. The perceptual colors can now be calculated based on the inputs and color appearance models, such as CIECAM [5, 6]. Also, the color discrimination abilities have been investigated and applied for developing the models [7, 8].

Recently, in addition to cones and rods, intrinsically photosensitive retinal ganglion cell (ipRGC) was found on the retina [9]. These cells have the visual pigment called *melanopsin* and respond to incident light stimuli. The ipRGC is also influenced by cones and rod inputs. The response time is slow, and the output is continuous. Also, ipRGC affects circadian rhythm and the occurrence of pupillary reflexes to light [9, 10].

The ipRGC affects not only the biological response but also visual perception. Brown et al. [11] studied the brightness perception related to ipRGC. They conducted an experiment using stimuli with different amounts of ipRGC stimulation without changing the amount of stimulation on cones. They used a multi-primary stimulus presentation device with four-color LEDs as the light source. As a result, they confirmed that as the stimulation level of ipRGC increased, the sense of brightness increased. Yamakawa et al. [12] formulated the brightness perception related to ipRGC. They conducted experiments using a stimulus presentation device with six primary colors. These results suggest that even if the metameric stimulus is colorimetrically equivalent (and the spectral distribution is different), the perception of brightness will differ.

As described in the previous studies, in order to investigate the effect of ipRGC on color perception, it is necessary to reproduce two metameric light stimuli (metameric ipRGC stimuli) that have the same amount of cones and rods stimulation, but different amount of ipRGC stimulation. It is significant to independently control the amount of ipRGC stimulation because the spectral sensitivity functions of the cones and rods overlap that of ipRGC in the wavelength band. However, researchers have not created metameric ipRGC stimuli due to the limitations of the number of primary colors. Then color perception and discrimination experiments for metameric ipRGC stimuli have not been conducted sufficiently.

In this study, as the preliminary experiment on metameric ipRGC stimuli, first, we propose a simple and accurate method for independently controlling ipRGC stimulation. Also, we clarify the range of chromaticity that can be presented by ipRGC metameric stimuli through the color discrimination experiments. Finally, we show discriminative color gamut due to metameric ipRGC stimuli.

Independent control of ipRGC stimuli using spectral basis

This section describes the method to control independent ipRGC stimulation in this study. Figure 1 shows the spectral sensitivity functions of LMS cones, rods, and ipRGCs. Here, spectral sensitives of LMS cones ($l(\lambda)$, $m(\lambda)$, and $s(\lambda)$) are derived from CIE2006LMS (22 years old, a 2-degree field of view). From these functions, the bases (e_1 to e_5) were obtained by orthonormalizing the L-cone, M-cone, S-cone, rod, and ipRGC in this order (Fig. 2). The spectral distribution $p(\lambda)$ of the light stimulus is created by a weighted linear sum using each basis e_1 to e_5 and coefficients ω_1 to ω_5 (Eq.1).

$$p(\lambda)=\omega_1 e_1(\lambda)+\omega_2 e_2(\lambda)+\omega_3 e_3(\lambda)+\omega_4 e_4(\lambda)+\omega_5 e_5(\lambda) \quad (1)$$

Where λ ranges from 380 nm to 700 nm. Here, the L-cone, M-cone, S-cone, rod, and ipRGC are orthonormalized in this order to obtain the basis. Therefore, the spectral sensitivity functions of the L-cone, M-cone, S-cone, rod, and ipRGC were calculated by using the basis and the coefficient matrix as follows:

$$[l(\lambda)\ m(\lambda)\ s(\lambda)\ r(\lambda)\ i(\lambda)] = [e_1(\lambda)e_2(\lambda)e_3(\lambda)e_4(\lambda)e_5(\lambda)] * \mathbf{M} \quad (2)$$

$$\mathbf{M} = \begin{pmatrix} 1 & 0.8046 & 0.0518 & 0.4946 & 0.3296 \\ 0 & 1 & 0.3310 & 1.5771 & 1.3412 \\ 0 & 0 & 1 & 0.4435 & 0.6118 \\ 0 & 0 & 0 & 1 & 1.1761 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

When the light stimulus $p(\lambda)$ is incident on the retina, the respective stimulus amounts of the L-cone, M-cone, S-cone, rod, and ipRGC (L, M, S, R, I) can be calculated using the spectral sensitivity functions and the spectral distributions of the light stimulus.

Since the bases e_1 to e_5 are orthonormal bases, using Equations1 and 2, L, M, S, R, and I can be expressed as follows:

$$\begin{aligned}[L\ M\ S\ R\ I] &= [l(\lambda)\ m(\lambda)\ s(\lambda)\ r(\lambda)\ i(\lambda)] * p(\lambda) \\ &= [e_1(\lambda)e_2(\lambda)e_3(\lambda)e_4(\lambda)e_5(\lambda)] * \mathbf{M} * \\ &\quad \{\omega_1 e_1(\lambda) + \omega_2 e_2(\lambda) + \omega_3 e_3(\lambda) + \omega_4 e_4(\lambda) + \omega_5 e_5(\lambda)\} \\ &= [\omega_1\ \omega_2\ \omega_3\ \omega_4\ \omega_5] * \mathbf{M}\end{aligned} \quad (3)$$

Therefore, the (relative) stimulus amount L, M, S, R, and I of each photoreceptor cell can be expressed by the following equations.

$$
\begin{aligned}
L &= \omega_1 \\
M &= 0.8046*\omega_1 + \omega_2 \\
S &= 0.0518*\omega_1 + 0.3310*\omega_2 + \omega_3 \\
R &= 0.4946*\omega_1 + 1.5771*\omega_2 + 0.4435*\omega_3 + \omega_4 \\
I &= 0.3296*\omega_1 + 1.3412*\omega_2 + 0.6118*\omega_3 + 1.1761*\omega_4 + \omega_5
\end{aligned} \tag{4}
$$

As shown in Equation 4, the amount of ipRGC stimulation depends on ω_5, which is the coefficient of the base e_5. Therefore, the spectral stimulus generated by changing the only ω_5 becomes an ipRGC metameric stimulus. Then, it becomes possible to control the amount of ipRGC stimulation independently.

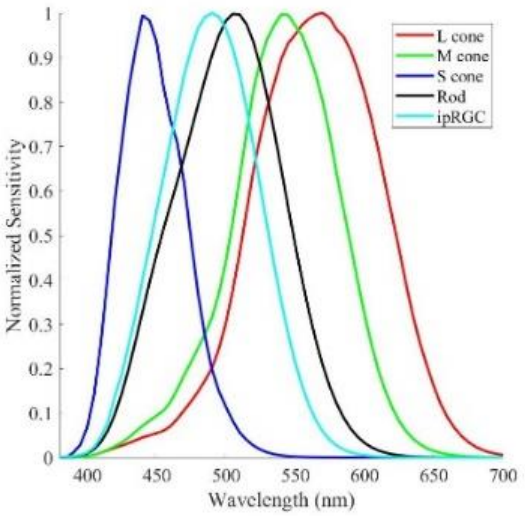


***Figure 1**. Spectral sensitivity function of the cone, rod, and ipRGC*

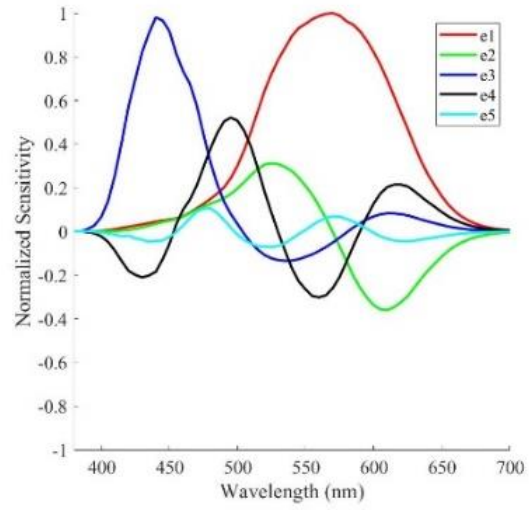


***Figure 2**. Orthonormal basis e_1 to e_5*

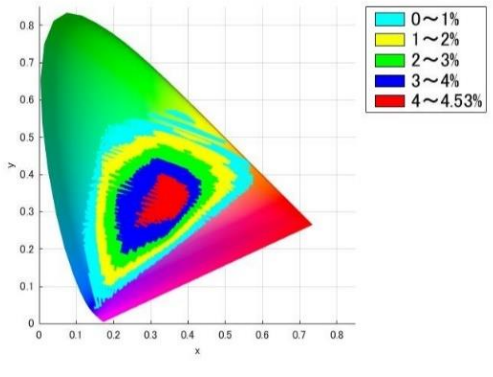


***Figure 3**. Chromaticity of metameric ipRGC stimuli. The only ipRGC can become as variables in the region. In the order of red, blue, green, yellow, and light blue, metameric amounts of ipRGC stimulation become larger.*

Color gamut simulation due to metameric ipRGC stimuli

As shown in orthonormal basis functions of Figure 2, since e_1 to e_5 contains negative values, a light stimulus $p(\lambda)$ often become negative values. A negative optical stimulus (spectral distribution) cannot be projected in the experiment. Therefore, it is necessary to find the presentable metameric ipRGC stimulus $p(\lambda)$, whose minimum value is 0 or more in the wavelength region. Figure 3 shows all non-negative ipRGC metameric stimuli (spectral distribution) plotted on a xy chromaticity diagram (using CIE2015XYZ). The color-coding indicates how much of the ipRGC alone can be changed. The color code indicates the percentage of changes that can be made only to ipRGC. (Light blue at 0 ~ 1% chromaticity, yellow at 1 ~ 2% chromaticity, green at 2 ~ 3% chromaticity, blue at 3 ~ 4% chromaticity, and red at 4% ~ 4.53% (maximum) chromaticity.)

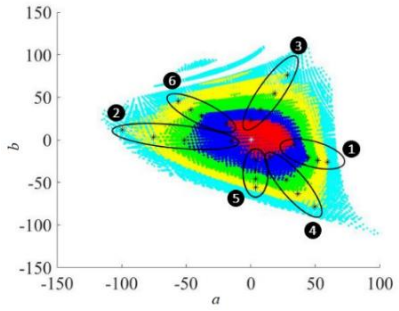
As shown in Figure 3, it can be confirmed that the closer the light stimulus to the white point, the more the amount of ipRGC stimulus can be controlled independently (in other words, the easier it is to create the ipRGC metameric stimulus). Also, the independent control of ipRGC is possible with more chromaticity in blue stimuli than in green and red stimuli.

Effect of metameric ipRGC stimulus on color discrimination

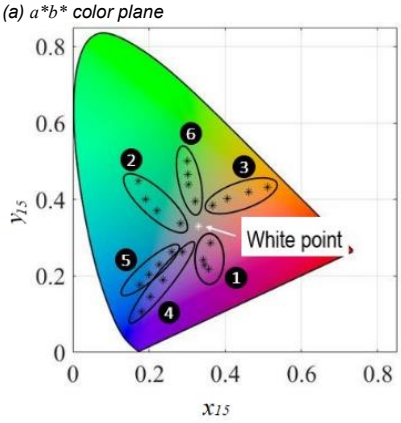
Experimental method

In this section, we investigate the effect of metameric ipRGC stimuli on color discrimination. We first converted the ipRGC metameric stimulus presentable range (Fig.3) to CIE L*a*b* space. Then, for the experimental stimuli, the following six groups were selected based on the hue of the converted chromaticity.

Group1. The maximum value of a (red to purple hue)
Group2. A minimum value of a (green hue)
Group3. b value is maximum (orange hue)
Group4. A minimum value of b (blue to purple hue)
Group5. Negative direction on b-axis (blue hue)
Group6. Approximately 45 degrees in the upper left (yellow-green hue)

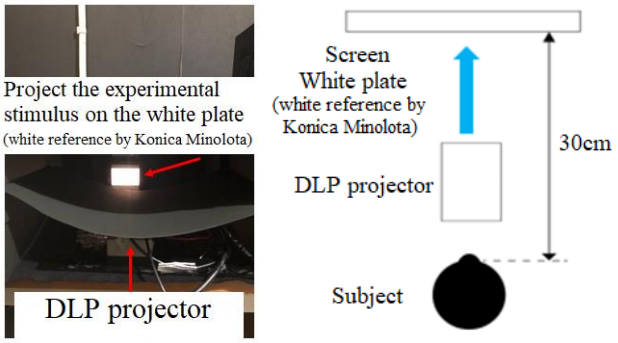


(a) a^*b^* color plane



(b) xy chromaticity diagram

Figure 4. *Experimental stimuli of 24 chromaticity points*



(a) Experiment environment (b) Bird's-eye view

Figure 5. *Experimental environment*

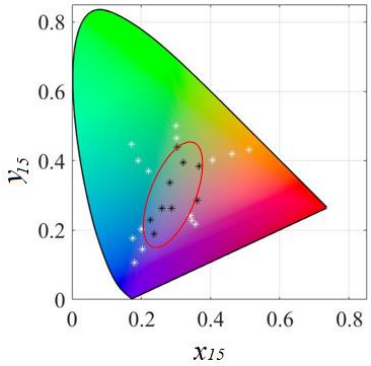


Figure 6*. Chromaticity of metameric ipRGC stimuli with color discrimination*

These groups are within the range where independent control of the ipRGC stimulation amount is possible by 1% or more. For each group, we selected 4 points from white point to highly saturated chromaticity. Figure 4 shows a plot of the 24 chromaticity points selected for the actual experimental stimuli on the a^*b^* plane and the xy chromaticity diagram. We measured the actual spectral distributions and CIELMS (CIEXYZ), rod, ipRGC values by a spectroradiometer. See also the appendices of figures for the spectral distributions of actual experimental stimuli, and of tables for the x, y, and Y values (luminance), rod stimulation, and ipRGC stimulation of actual experimental stimuli.

Figure 5 shows the experimental environment. We experimented in a dark room. We created experimental stimuli with a multi-primary image projector (DLP projector) [13] and projected on a white plate (a white reference made by Konica Minolta). The distance from the stimulus presentation position (white version) to the subject was 30 cm. The stimulus was a rectangle measuring 3 cm long and 5 cm wide. The subject looked at the center of the stimulus.

We conducted experiments with each of the 24 points on the xy chromaticity diagram. There were two types of evaluation stimuli; the maximum metameric ipRGC stimulus that maximizes the amount of ipRGC stimulation at each chromaticity point, and the dummy stimulus that was the same as the reference. After the reference stimulus (the minimum metameric ipRGC stimulus) was presented, ipRGC metameric stimuli or dummy stimuli were presented randomly. The subjects (five males of twenties with normal color vision) replied which one felt the difference in color appearance compared to the reference stimulus. In this experiment, if color discrimination is not possible, the correct answer rate will become 50%.

Experimental results

Figure 6 shows the results of the color discrimination experiment for the experimental stimuli Group1 to Group6 of each hue, fitted with a logistic function. The horizontal axis of each figure shows the difference between the reference stimulus and the metameric ipRGC stimulus. (This stimulus value is defined as 100 for the ipRGC stimulus amount for white light whose spectral distribution is all 100 in the wavelength range. See also the appendices of the tables) Also, as the value on the horizontal axis in Figure 6 increases, the stimulus becomes closer to white. The vertical axis is the rate at which the subject perceived a difference in appearance between the reference stimulus and the ipRGC metameric stimulus.

Discussions

Figure 7 is a xy chromaticity diagram in which the experimental results are plotted. We plot black circles as the chromaticity that more than half of the subjects were able to discriminate between the reference stimulus and the ipRGC metameric stimulus. On the other hand, we plot white circles as the chromaticity for which color discrimination was not possible. As shown in Figure 7, even if the CIEXYZ values are the same, the closer to the white point, the more likely it is that changes in ipRGC stimulus will cause the difference in color appearance. Also, red and orange hues have little effect on color discrimination by ipRGC.

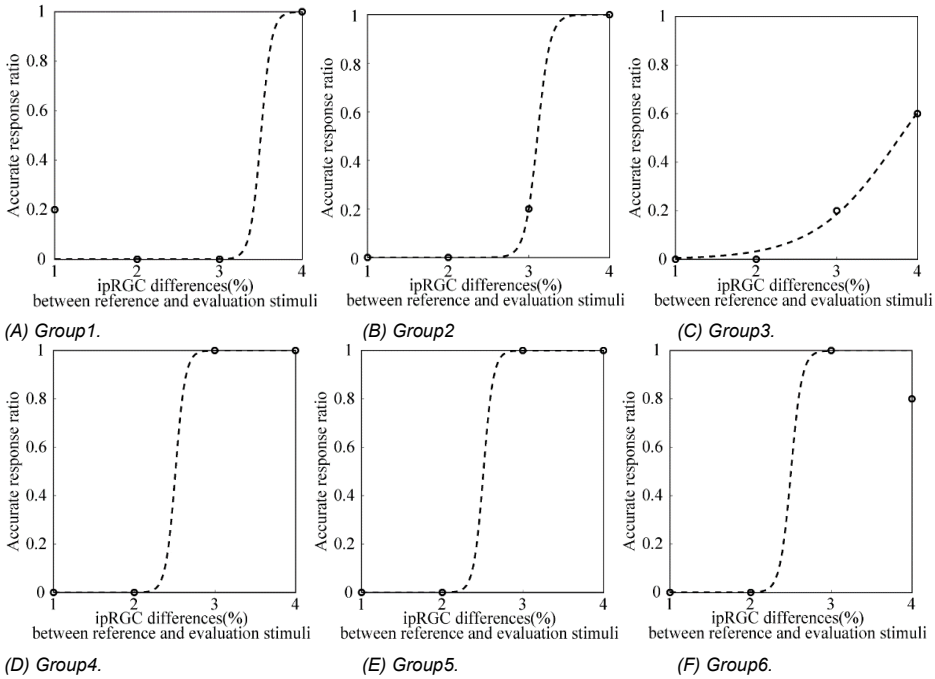


***Figure 6**. Results of color discrimination experiment. The chromaticity of ipRGC difference = 1% means far from the white point, and that of ipRGC difference = 4% means close to the white point.*

Conclusions

The purpose of this study was to clarify the effect of metameric ipRGC stimuli on the chromaticity range and color discrimination. For achieving this goal, first, we proposed a method to control the amount of ipRGC stimulation independently. Then, we showed the color gamut due to metameric ipRGC stimuli. Second, we conducted color discrimination experiments. The results suggested that the higher the lightness and the closer the hue is to blue, the easier it is to present the ipRGC metameric stimulus, and the higher the effect of ipRGC on color discrimination. Furthermore, it was suggested that the closer to the white point, the higher the effect of ipRGC on color perception may be. As future work, in the area where color discrimination is possible, we investigate whether ipRGC affects the difference in the appearance of hue, lightness, and saturation.

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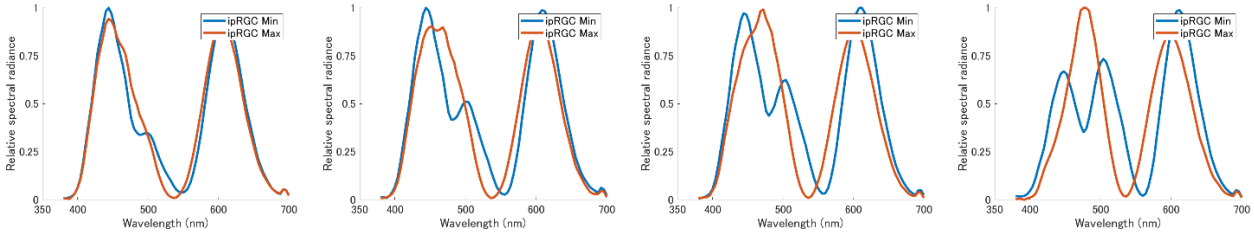
Author Biography

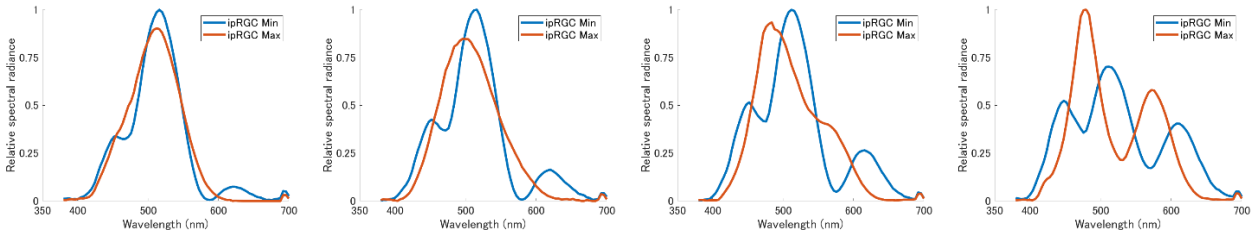
Masaya Ohtsu is currently a student of a bachelor's course program in the Department of Information Sciences, Chiba University. His research interests are color perception, spectral imaging, color engineering. Especially, he is now working for investigating the relationship between ipRGC and color perception using a multi-spectral camera and projector.

Appendix

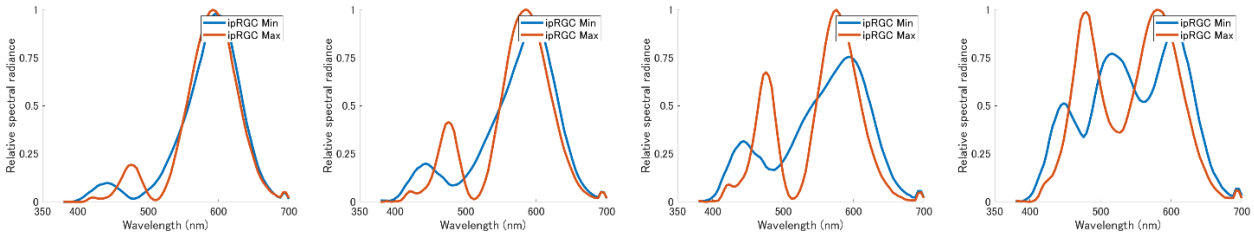
The spectral power distributions and x, y, and Y values (luminance), rod stimulation, and ipRGC stimulation.



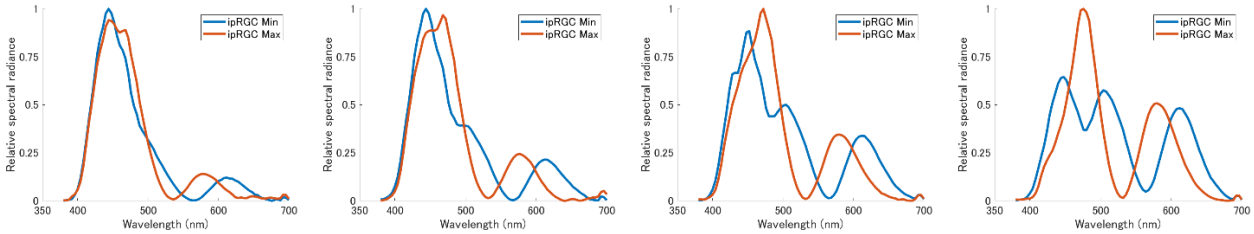
Metameric ipRGC stimuli of Group 1: from left to right: far from white point (ipRGC difference: 1%) ~ close to white point (ipRGC difference: 4%)



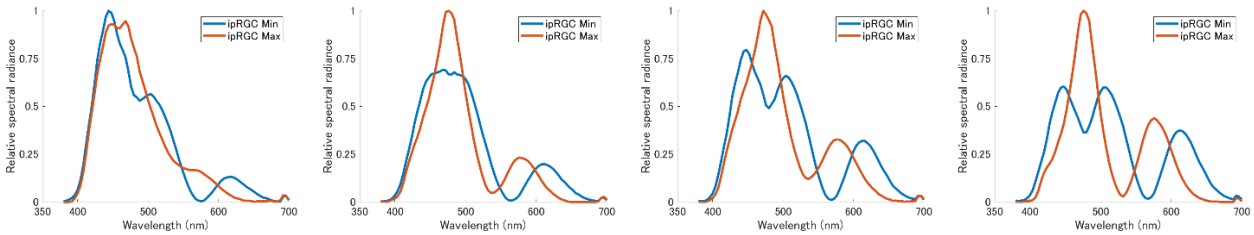
Metameric ipRGC stimuli of Group 2: from left to right: far from white point (ipRGC difference: 1%) ~ close to white point (ipRGC difference: 4%)



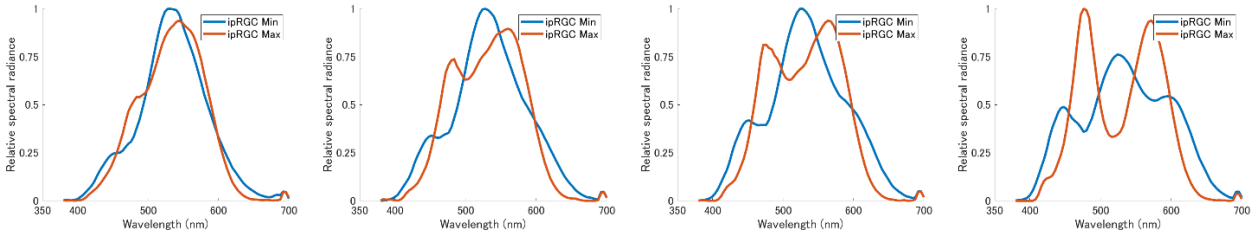
Metameric ipRGC stimuli of Group 3: from left to right: far from white point (ipRGC difference: 1%) ~ close to white point (ipRGC difference: 4%)



Metameric ipRGC stimuli of Group 4: from left to right: far from white point (ipRGC difference: 1%) ~ close to white point (ipRGC difference: 4%)



Metameric ipRGC stimuli of Group 5: from left to right: far from white point (ipRGC difference: 1%) ~ close to white point (ipRGC difference: 4%)



Metameric ipRGC stimuli of Group 6: from left to right: far from white point (ipRGC difference: 1%) ~ close to white point (ipRGC difference: 4%)

***Figure A**. Spectral distribution of actual metameric ipRGC stimuli in the experiments (measured by a spectroradiometer)*

Table A. x, y, Y, Rod, and ipRGC stimulation amount of actual experimental stimuli (measured by a spectroradiometer). The rod and ipRGC stimuli value are defined as 100 for the white light whose spectral distribution is all 100 in the wavelength range. The measured ipRGC values are slightly different from the % notations on the upper side of the table. This is because of the difference between measured and computer-simulated spectra in the calibration of the spectral stimuli calibration.

Group1

Chromaticity point	ipRGC diff. = 1%		ipRGC diff. = 2%		ipRGC diff. = 3%		ipRGC diff. = 4%	
ipRGC	Min	Max	Min	Max	Min	Max	Min	Max
x_{15}	0.353	0.353	0.344	0.343	0.340	0.339	0.365	0.364
y_{15}	0.226	0.227	0.236	0.235	0.249	0.249	0.296	0.295
Y[cd/m^2]	6.67	6.81	4.05	4.12	4.48	4.49	5.39	5.43
Rod (%)	36.3	36.8	41.6	42.1	48.2	47.4	46.6	47.7
ipRGC (%)	42.5	43.9	47.6	50.2	54.1	56.0	49.7	55.0

Group2

Chromaticity point	ipRGC diff. = 1%		ipRGC diff. = 2%		ipRGC diff. = 3%		ipRGC diff. = 4%	
ipRGC	Min	Max	Min	Max	Min	Max	Min	Max
x_{15}	0.178	0.177	0.195	0.194	0.225	0.224	0.285	0.284
y_{15}	0.459	0.455	0.409	0.408	0.378	0.377	0.344	0.342
Y[cd/m^2]	5.20	5.25	5.04	5.08	7.69	7.70	6.71	6.74
Rod (%)	59.1	59.2	60.2	60.4	62.7	64.0	50.0	50.2
ipRGC (%)	57.2	58.4	59.6	61.9	62.8	67.2	50.4	54.7

Group3

Chromaticity point	ipRGC diff. = 1%		ipRGC diff. = 2%		ipRGC diff. = 3%		ipRGC diff. = 4%	
ipRGC	Min	Max	Min	Max	Min	Max	Min	Max
x_{15}	0.513	0.513	0.466	0.464	0.410	0.409	0.371	0.369
y_{15}	0.429	0.429	0.418	0.417	0.401	0.399	0.388	0.386
Y[cd/m^2]	14.8	14.8	16.1	16.1	13.4	13.3	11.4	11.5
Rod (%)	15.2	15.0	24.3	24.5	31.6	31.7	58.6	59.0
ipRGC (%)	9.9	10.8	18.8	20.9	27.1	30.2	55.2	59.6

Group4

Chromaticity point	ipRGC diff. = 1%		ipRGC diff. = 2%		ipRGC diff. = 3%		ipRGC diff. = 4%	
ipRGC	Min	Max	Min	Max	Min	Max	Min	Max
x_{15}	0.174	0.175	0.199	0.197	0.235	0.234	0.288	0.286
y_{15}	0.118	0.120	0.156	0.154	0.201	0.197	0.271	0.270
Y[cd/m^2]	1.66	1.73	2.46	2.48	4.64	4.49	5.41	5.43
Rod (%)	35.1	35.6	35.7	35.6	43.3	41.5	41.9	42.3
ipRGC (%)	43.6	45.2	42.5	44.3	49.6	50.6	45.3	49.6

Group5

Chromaticity point	ipRGC diff. = 1%		ipRGC diff. = 2%		ipRGC diff. = 3%		ipRGC diff. = 4%	
ipRGC	Min	Max	Min	Max	Min	Max	Min	Max
x_{15}	0.171	0.171	0.197	0.198	0.226	0.225	0.260	0.258
y_{15}	0.187	0.186	0.218	0.215	0.240	0.237	0.271	0.269
Y[cd/m^2]	3.80	3.87	4.38	4.28	6.61	6.49	6.14	6.09
Rod (%)	38.0	37.8	44.8	43.9	49.5	48.9	42.1	41.8
ipRGC (%)	43.4	44.4	51.6	52.6	54.8	57.2	45.4	49.1

Group6

Chromaticity point	ipRGC diff. = 1%		ipRGC diff. = 2%		ipRGC diff. = 3%		ipRGC diff. = 4%	
ipRGC	Min	Max	Min	Max	Min	Max	Min	Max
x_{15}	0.309	0.308	0.309	0.308	0.310	0.311	0.325	0.324
y_{15}	0.501	0.500	0.467	0.465	0.442	0.442	0.396	0.395
Y[cd/m^2]	24.3	24.2	24.4	24.3	24.6	24.5	16.1	16.2
Rod (%)	60.3	60.1	62.4	62.2	66.9	65.8	56.1	56.4
ipRGC (%)	52.2	53.2	55.8	57.7	61.0	62.6	52.6	56.9

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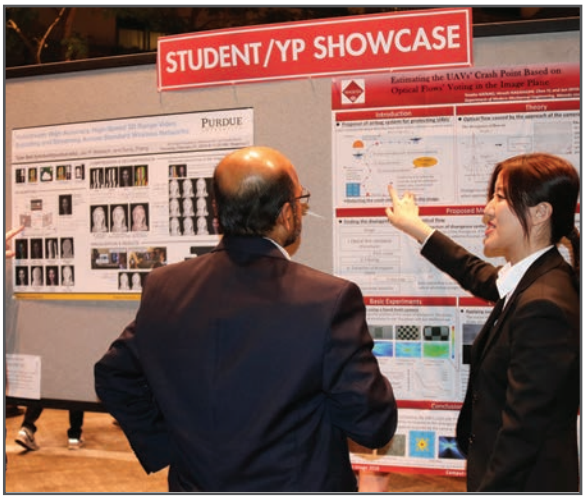

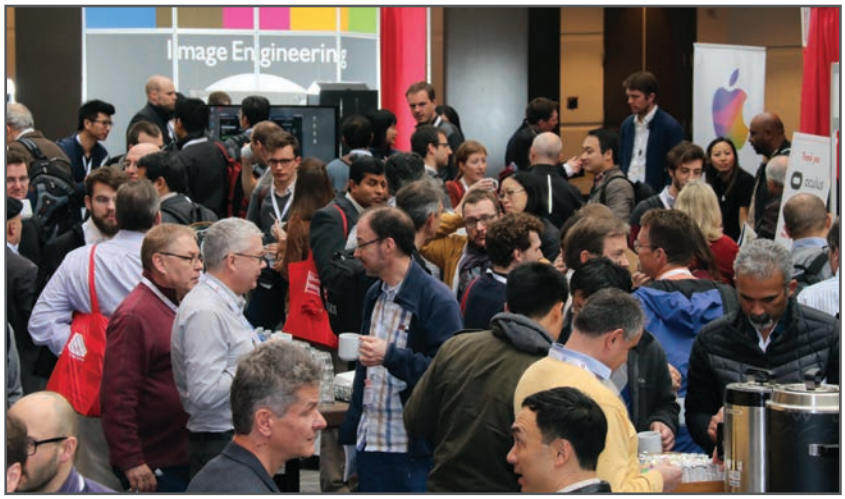

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