# Display Color Comparison based on ipRGC Response Differences using Metameric Black

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**ABSTRACT**

*This study investigated the impact of ipRGC on color discrimination between displays. We calculated and compared the amount of ipRGC stimuli of metameric color pairs on displays using the metameric black paradigm. The results showed that ipRGC might affect the color visibility of several display pairs.*

## 1 INTRODUCTION

Even though we observe two displays with different RGB basis sets after color matching or color calibration, display color appearances are sometimes different between displays. Several studies [1,2,3] had claimed that color reproduction fails due to differences in RGB basis sets. They suggested that accurate color reproduction cannot be performed with only three basis sets.

Recently, intrinsically photosensitive retinal ganglion cell (ipRGC), a different photoreceptor than cones and rods, was discovered [4]. ipRGC contains the intrinsic photoreceptor melanopsin, which has a spectral sensitivity function that peaks around 488 nm. Previous studies have reported that ipRGC affects the regulation of circadian rhythms and pupil counter-reflections and was thought not to affect visual perception [5]. However, recent studies have suggested that ipRGC also affects color perception [6,7]. A recent study conducted color discrimination experiments by creating ipRGC metameric stimuli in which stimuli to the cones and rods were not altered, but only to the ipRGC [8]. The results suggested that ipRGC affects color discriminations in some color stimuli. In other words, metameric stimulus pairs created by different RGB basis sets may appear differently in color depending on the ipRGC, even if the tristimulus values are the same.

In 1953, Wyszecki [9, 10] proposed the metameric black paradigm. The metameric black paradigm can decompose arbitrary stimuli into basic metamers that are involved in the color specification and metameric blacks that are not involved in the color specification. Viénot et al. [11] used the metameric black paradigm to investigate the range of excitation of ipRGC and rods at certain chromaticities. The use of metameric black allows us to efficiently study photoreceptors, which have been considered unrelated to color perception in previous studies.

In this study, we use the metameric black paradigm to investigate the effect of ipRGC on color discrimination between displays. Specifically, we first use two displays with different RGB basis sets to create a metameric stimulus pair with the same tri-stimulus value. Next, the metameric black is calculated from each stimulus. Finally, the ipRGC stimulus is calculated from the metameric black and compared to them.

## 2 RELATED STUDIES and PROPOSED APPROACH

### 2.1 Effect of ipRGC on color perception

In a recent study [8], we proposed a method to control the amount of ipRGC in the light source and investigated the effect of ipRGC on color discrimination. In the study, we defined the ipRGC stimulus $I$ (%) of the spectral distribution $p(\lambda)$ as Equation 1.

$$I = 100\frac{\int_{380}^{700} p(\lambda)i(\lambda)d\lambda}{\int_{380}^{700} p_w(\lambda)i(\lambda)d\lambda}, \quad (1)$$

where $i(\lambda)$ is the spectral sensitivity function of ipRGC and $p_w(\lambda)$ is the spectral distribution of white light, which is all 100 in the wavelength range. The controllable range of ipRGC stimuli was different for each tri-stimulus value. In particular, when a metameric color pair is close to the white point, the difference of the amount of ipRGC stimuli between the metameric colors can be controlled larger.

In addition, we constructed an ipRGC metameric stimulus pair with ipRGC control for each color stimulus and conducted color discrimination experiments. The results suggested that the ipRGC metameric stimulus pair could cause color discriminations in the chromaticity range enclosed by the red circles in Figure 1. We also found the color discrimination due to ipRGC was caused when the ipRGC stimuli differences between metameric color pairs are more than 2%.

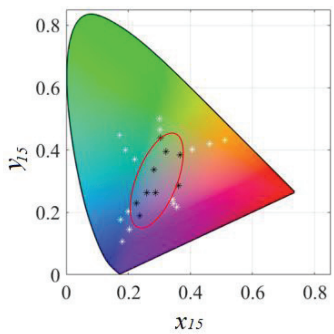



**Fig.1. Chromaticity of metameric ipRGC stimuli with color discrimination**

### 2.2 Metameric Black Paradigm

The metameric black paradigm was invented by Wyszecki in 1953 [9]. Wyszecki hypothesized that human visual processing is processed using only a part of the spectral component.

In 1982, based on Wyszecki's hypothesis, Cohen and Kappauf [10] stated,

1. The spectral components $\mathbf{C}$ can be decomposed into basic metamers $\mathbf{C}^*$, which affect human color perception processing, and metameric black $\mathbf{B}$, which does not affect color perception processing (Equation 2).

$$\mathbf{C} = \mathbf{C}^* + \mathbf{B}. \quad (2)$$

2. The basic metamer C and metameric black B can be expressed as Equation 3 and Equation 4.

$$\mathbf{C}^* = \mathbf{P_V}\mathbf{C}, \quad (3)$$

$$\mathbf{B} = (\mathbf{I} - \mathbf{P_V})\mathbf{C}, \quad (4)$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{P_V}$ is the direct projection into visual space, which can be expressed as in Equation 5 using the CIE color matching function matrix $\mathbf{A}$.

$$\mathbf{P_V} = \mathbf{A}(\mathbf{A}^t\mathbf{A})^{-1}\mathbf{A}^t. \quad (5)$$

The method for calculating ipRGC stimulation using metameric black shows the effect of ipRGC on the metamerism of the spectral components.

### 2.3 Comparison of ipRGC stimulus using metameric black

When the color stimuli output from two displays (Display 1 and Display 2) are isochromatic, these spectral distributions $\mathbf{C_1}$ and $\mathbf{C_2}$ can be expressed as Equation 6 and Equation 7.

$$\mathbf{C_1} = \mathbf{C}^* + \mathbf{B_1}, \quad (6)$$

$$\mathbf{C_2} = \mathbf{C}^* + \mathbf{B_2}, \quad (7)$$

where $\mathbf{C}^*$ is the common metamer and $\mathbf{B_1}$, $\mathbf{B_2}$ are the respective metameric blacks.

From the metameric black paradigm, $\mathbf{B_1}$ and $\mathbf{B_2}$ are elements that do not affect color perception processing, i.e., elements with a tri-stimulus value (X,Y,Z) = (0,0,0). However, if ipRGC affect color perception, we can calculate the difference in ipRGC stimulus values using $\mathbf{B_1}$ and $\mathbf{B_2}$ as shown in the Equation 8.

$$ipRGC_{difference} = \left| 100 \frac{\int_{380}^{700} (C_1(\lambda) - C_2(\lambda))\, i(\lambda) d\lambda}{\int_{380}^{700} p_w(\lambda) i(\lambda) d\lambda} \right| = \left| 100 \frac{\int_{380}^{700} (B_1(\lambda) - B_2(\lambda))\, i(\lambda) d\lambda}{\int_{380}^{700} p_w(\lambda) i(\lambda) d\lambda} \right| \quad (8)$$

where $C(\lambda)$ and $B(\lambda)$ indicate functions, which are equal to $\mathbf{C}$ and $\mathbf{B}$ in Equation 2.

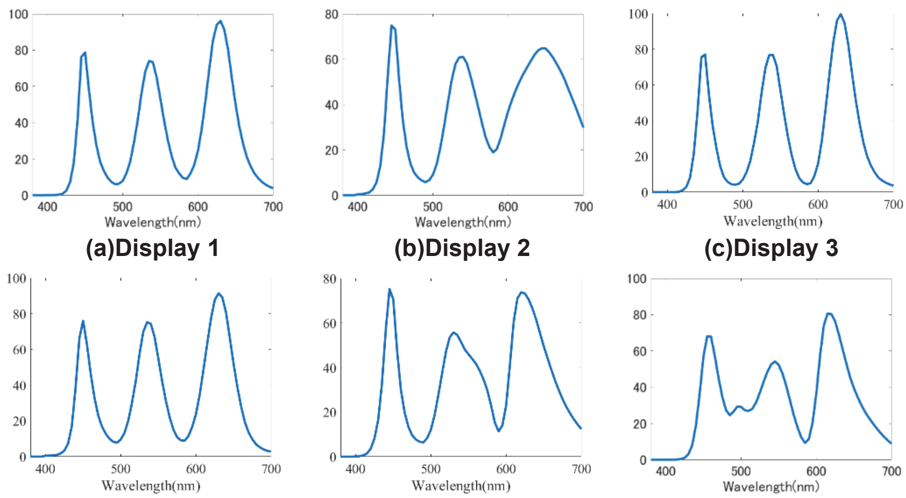
## 3 EXPERIMENT

In this section, we describe our experiments to investigate the effect of ipRGC on color discrimination between displays.

### 3.1 Method

We tested six commercial displays. Five of those monitors are liquid crystal displays (LCDs) with RGB primaries as Display 1 to 5, and one RGBW OLED as Display 6.

First, we create the stimulus with the largest independently controllable range of ipRGC stimulus ($(x, y) = (0.367, 0.357)$) from the RGB spectral power distribution. Figure 3 shows the spectral distribution of the stimulus. Second, we create Metameric blacks from these spectral distributions. We used the color-matching function (22 years old, a 2-degree field of view) and the ipRGC spectral sensitivity function shown in Figure 4. Figures 5 and 6 show the basic metamer of the stimulus and metameric black of the stimulus, respectively. Since the tri-stimulus values of all the color stimuli are the same, the basic metamers (shown in Figure 5) of all the color stimuli are identical. Finally, we calculate the ipRGC stimulus from metameric blacks, and compared them. If the differences between ipRGC stimuli are more than 2%, ipRGC might affect the color discriminations between displays.




(a)Display 1 (b)Display 2 (c)Display 3

(d)Display 4 (e)Display 5 (f)Display 6

**Fig.3 Spectral distributions of metameric color stimuli ( $(x,y)$=(0.367,0.357) ), which are equal to $\mathbf{C}$ in Equation 2.**

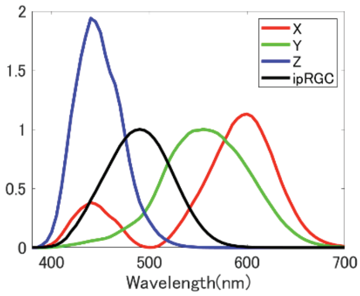



**Fig.4 Color-matching functions and ipRGC spectral sensitivity function**

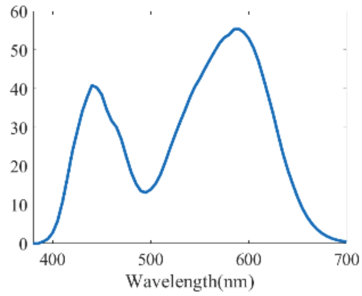
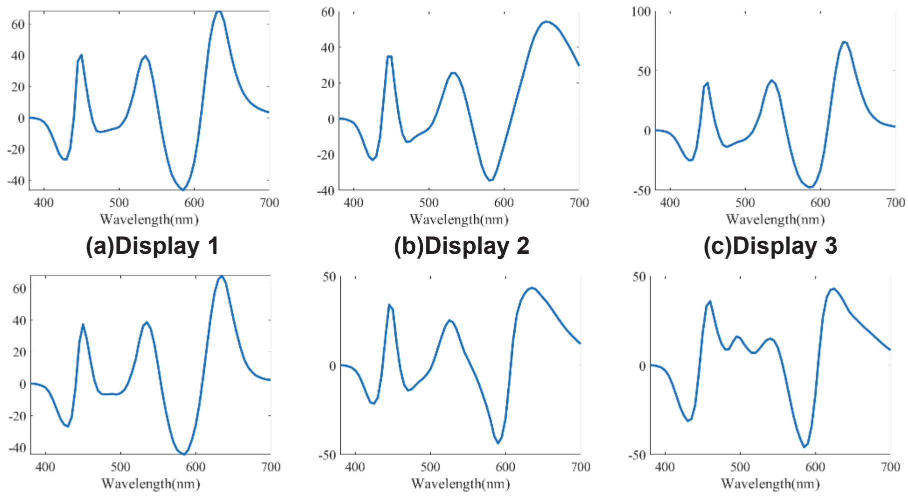



**Fig.5 Basic metamer of the stimulus, which are equal to $\mathrm{C}^*$ in Equation 2.**




**(a)Display 1** **(b)Display 2** **(c)Display 3**

**(d)Display 4** **(e)Display 5** **(f)Display 6**

**Fig.6 Metameric black of metameric color stimuli, which are equal to $\mathrm{B}$ in Equation 2.**

**Table.1 Comparison of ipRGC stimulus difference between displays**

| Display Pair | ipRGC Stimuli Difference (%) |
|---|---|
| **1-2** | **2.08** |
| 1-3 | 1.24 |
| 1-4 | 0.44 |
| 1-5 | 1.30 |
| **1-6** | **6.52** |
| 2-3 | 0.84 |
| **2-4** | **2.52** |
| 2-5 | 0.78 |
| **2-6** | **8.60** |
| 3-4 | 1.68 |
| 3-5 | 0.06 |
| **3-6** | **7.76** |
| 4-5 | 1.74 |
| **4-6** | **6.08** |
| **5-6** | **7.82** |

### 3.2 Result

Table 1 shows the difference in the amount of ipRGC stimulation between each display. Values with a difference in ipRGC stimulation of 2% or more for each display are indicated in bold. These results suggest that ipRGC may affect color discrimination between some displays. In addition, the difference in the amount of ipRGC stimulation between Display 6 (RGBW primaries) and other displays (RGB primaries) is particularly large. This suggests that certain displays may be significantly affected by ipRGC, and that ipRGC should also be considered when defining the RGB basis set of a display.

## 4 DISCUSSIONS

### 4.1 Comparison of a display to real objects

As described in Section 2.1, The changeable range of ipRGC stimuli was different for each of the tri-stimulus value. For the stimuli in this study ($(x, y) = (0.367, 0.357)$), the changeable range of the ipRGC stimulus is about 35%. Therefore, ipRGC might also influence color discriminations between displays and real objects, even though display colors are completely calibrated.

### 4.2 Consideration of rod stimulus

In this study, we did not consider the effect of rods on color perception. The changeable range of the ipRGC stimulus described so far ignores the rod stimulus. When the rod body stimulus was considered, the changeable range of ipRGC stimulus for metameric colors was 4.53%. Therefore, it would be difficult to change the ipRGC stimulus by more than 3%. In future work, it will be necessary to consider the effect of the weak light (light to which the rods respond) produced by the display.

## 5 CONCLUSIONS

In this study, we investigated the effect of ipRGC on color discrimination between displays using the metameric black paradigm. We created light stimuli with identical tristimulus values in each display and compared the ipRGC stimuli calculated from the metameric black of each stimulus. The results suggested that it could affect the color visibility of some display pairs. Future experiments will be conducted on subjects to investigate whether ipRGCs affect color discrimination in subjects.

## ACKNOWLEDGEMENTS

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