Observer metamerism: Why do [mis]matches of neutral appear pinkish or greenish?

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Abstract

White lighting and neutral-appearing objects are essential in numerous color applications. In particular, setting or tuning a reference white point is a key procedure in both camera and display applications. Various studies on observer metamerism pointed out that noticeable color disagreements between observers mainly appear in neutral colors. Thus, it is vital to understand how observer metamers of white (or neutral) appear in different colors by different observers. Most observers who participated in a visual demonstration reported that white observer metamers appear pinkish or greenish but rarely yellowish or bluish. In this paper, this intriguing question, "Why observer metamers of white are usually pinkish or greenish?," is addressed based on simulations. Besides, it is also analyzed that which physiological factors play an essential role in this phenomenon and why it is less likely for humans to perceive yellowish or bluish observer metamers of white.
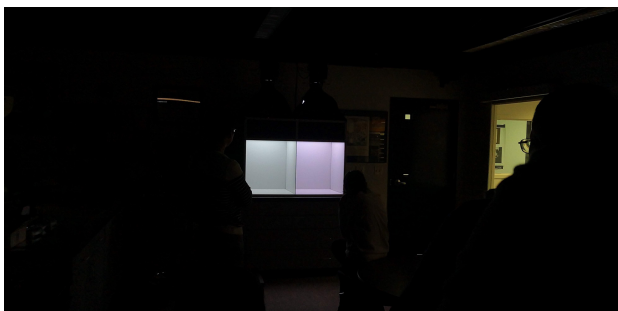
Introduction

Figure 1: A photo of a neutral metamer for an observer out of the Asano's 10 categorical observers [1] with a field of view (FOV) of 10°. Note that the two light booths would theoretically appear the same D65 white for the observer. However, due to the camera's RGB sensitivity, the light booth on the right appears pinkish or purplish. Also, if the image was white-balanced for the light booth on the right, the light booth on the left might appear greenish.

It is not uncommon to see two spectrally different stimuli match in color for an observer. At the same time, the stimuli pair likely no longer match for other observers. This phenomenon is called observer metamerism. Observer metamerism intrinsically occurs due to differences in the color matching functions (CMFs) of different observers [2]. The CMFs of an observer are, indeed, derived by characterizing the spectral sensitivities of his/her visual system [3]. Importantly, the spectral sensitivities are determined by different physiological factors, such as lens pigment, macular pigment, and three types of photopigments (L, M, and S-cone) [4, 5].

An interesting visual demonstration regarding observer metamerism was held at the Munsell Color Science Laboratory of Rochester Institute of Technology. A pair of light booths were designed to illuminate metamers for a given observer. The light booths adopted the same light source, which has seven narrow-
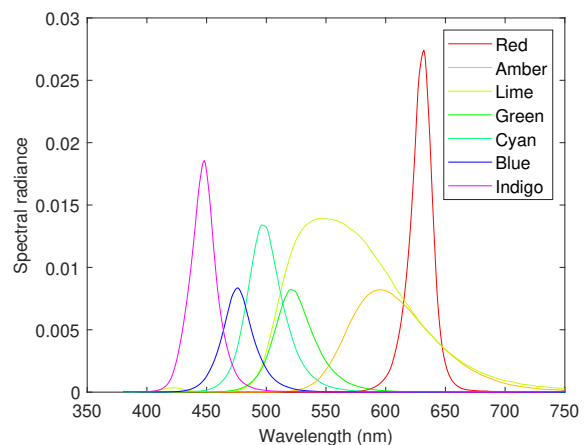

Figure 2: Spectral power distributions of the 7-primary LED system used in the visual demonstration in Figure 1. Note that the names of the 7-primaries were determined by the manufacturer [6].

band primaries but used different combinations of the primaries. Specifically, the light booth on the participants' left was tuned to illuminate the CIE D65 using the seven primaries for the CIE 10° observer [5]. On the other hand, the light booth on the participants' right was tuned to appear the same using four out of the seven primaries for a given observer. For the demonstration, 10 categorical observers devised by Asano were used [1]. It means that 10 metamers were, in turn, presented to the participants, and the participants were asked whether the two light booths illuminate the same white and what color they see from the two light booths if they do not match in color. Figure 1 represents one of the metamers in the visual demonstration. Interestingly, by the smartphone camera used to take the photo, the light booth on the right appears pinkish while the light booth on the left appears neutral. However, it is noteworthy that the light booth on the right appeared greenish for some participants. At the same time, some participants argued that none of the light booths appears neutral, and the color of the light booth on the left changes over the demonstration even though the light booth on the left remained unchanged during the whole demonstration. It means that neutral sensation relies on not only observers but also stimuli paired. Another noteworthy is that very few people answered the light booths appear yellowish or bluish. This casual experiment cast an intriguing question that "Why do mismatches of neutral (or white) usually appear either pinkish or greenish?".

This paper aims to address the question based on simulations. First of all, this paper explores whether the observations in the demonstration are valid or probable. The article suggests the answer to the intriguing question, explaining which physiological factors mainly contributed to the phenomenon. The paper also indicates whether people can perceive neutral observer metamers as bluish or yellowish.

Procedure

To simulate the phenomenon, a simulation GUI was implemented using MATLAB R2019b, as shown in Figure 3. The GUI shows four plots on the left side. The two plots on the top-left represent the cone fundamentals and XYZ-like color matching functions (CMFs) of two observers, reference observer, and individual observer. The reference observer was fixed as the CIE 10° standard observer.

The cone fundamentals and XYZ-like CMFs of the reference observer are plotted with solid lines. On the other hand, the cone fundamentals and XYZ-like CMFs of the individual observer, which are plotted with dotted lines, are adjustable using either the slide bars for 8 physiological parameters: Lens density (Lens), Peak optical density in Macula (Macula), Peak optical density in L photopigment (PL), Peak optical density in M photopigment (PM), Peak optical density in S photopigment (PS), Peak wavelength shift in L photopigment (SL), Peak wavelength shift in M photopigment (SM), and Peak wavelength shift in S photopigment (SL), and age or the drop-down boxes to select a categorical observer predefined. The ranges of the physiological parameters and age (20 - 80) are based on the work of Asano [7], as described in Table 1. The maximum range of each physiological parameter adjustable on the GUI is [-3σ +3σ]. The two plots on the bottom-left represent the spectral power distributions (SPDs) of a reference stimulus and device under test (DUT). It is assumed that the test display is used to reproduce a color match of the reference stimulus for the reference observer. In this work, the SPD of the CIE D65 illuminant was used as the reference stimulus, while two virtual displays as shown in Figure 4, a broad-band primary display and narrow-band primary display, which can cover the Rec.709 and Rec.2020, respectively, were assumed as test display. Additionally, all the possible 3+ primary combinations, which represent a D65 metamer for the reference observer, from the 7-primary LED system were added to the test display list. A total of 67 different 3+ primary combinations were created and these primary combinations particularly aimed to investigate whether the pinkish-greenish variation could be extensively witnessed across various displays.

The Hue-Chroma polar-scatter, which is based on the a*-b* plane of the CIELAB color space, visualizes the discrepancy in the color reproduced on the test display between the reference observer and individual observers. Thus, the polar-scatter plot in Figure 3 implies that the color on the test display appears neutral for the reference observer while it appears pinkish for the individual observer. More precisely, the color that the individual observer sees is a Δ a*b* of 24.7 away at 319° from the neutral color. Also, the color discrepancy can be examined in the CIE u'v' chromaticity diagram on the other tab menu. But, note that the background color in the polar-scatter is exaggerated for visualization, which means that the color does not accurately represent what the observers, indeed, perceive.

Results and Discussion

The pinkish-greenish variation

First of all, a simulation was performed to see whether the pinkish-greenish variation exists. For the simulation, the 10 categorical observers were used because categorical observers could represent the inter-observer variability of color-normal populations [1, 8]. The simulation created a pair of the CIE D65 metamers for the CIE 10° standard observer on the two displays. Then, what colors on the two displays look like for the 10 categorical observers were simulated, as shown in Figure 5.

A difference in the magnitude of a color discrepancy was found between the two displays. Nonetheless, Figure 5 clearly represents the pinkish-greenish variation regardless of the displays. It reveals that inter-observer variability could be intensified on narrow-band primary displays. In order to make sure whether the pinkish-greenish variation could be extensively witnessed across different sets and numbers of primaries, the same simulation was conducted for the 67 3+ primary combinations.

The two plots in Figure 6 represent the normalized cumulative magnitudes from the simulation result. Despite the fact that some primary combinations barely show the pinkish-greenish variation, a quite consistent tendency was observed across the primary combinations. The primary combinations, which do not show a clear pinkish-greenish variation, commonly represented a low degree of observer metamerism. Thus, this simulation result indicates that in every case where there is a mismatch of noticeable magnitude, it is consistently in the pinkish-greenish direction.

Another simulation was carried out to look at what causes the pinkish-greenish variation by computing the degree of the effects of each of the individual 8 physiological parameters and age on the color variation. The simulation result is noteworthy. First, as shown in Figure 7, the majority of the 8 physiological parameters including age are actively involved in the pinkish-greenish variation except for 4 parameters: Peak wavelength shift in L and M cones (SL and SM) and peak optical density in L and M cones (PL and PM). Instead, these 4 parameters likely cause another color variation, such as a reddish-cyanish variation. Another notable finding is that the effects of all the physiological parameters and age decrease on the broad-band primary display. In particular, the exceptional four parameters become barely effective on the broad-band primary display. Indeed, this change makes sense as the degree of observer metamerism tends to decrease with increasing the spectral bandwidth of color stimuli. Nonetheless, it should be also noted that lens density and age are the two biggest effects. It is plausible because the lens density particularly tends to be the largest source of individual variation even within an age group. Besides, the simulation result also shows that these two parameters obviously move along with the pinkish-greenish variation, and they are dominant enough to take over the effects of the other parameters. To be more precise, increasing lens density (towards the direction of positive standard deviations) or/and age results in the pinkish variation. On the other hand, decreasing lens density (towards the direction of negative standard deviations) or/and age arises the greenish variation. Also, it is interesting to see that all these parameters move along constant hue lines as the parameters increase or decrease. For example, as in Figure 7-(a), a lens density of 3 σ distance from the mean (center) is on the same hue line as a lens density of 1 σ and 2 σ.

This finding indeed underpins what we additionally found from the simulation result on all the possible primary combinations. Figure 8 illustrates color variations on the two different primary combinations, a 3-primary combination, and 5-primary combination. It shows that the two primary combinations result in the pinkish-greenish variation. Besides, interestingly, the observers clustered into four groups were found from more than half of the primary combinations. This clustering is likely attributed to the two primary parameters, lens density, and age, as described in Table 1. For example, all four observers in Group #1 are the 30s, and their lens densities are commonly less than those mean value. On the other hand, the three observers in Group #2 are similar ages as Group #1; however, their lens densities are larger than those mean value. Again, these results emphasize that
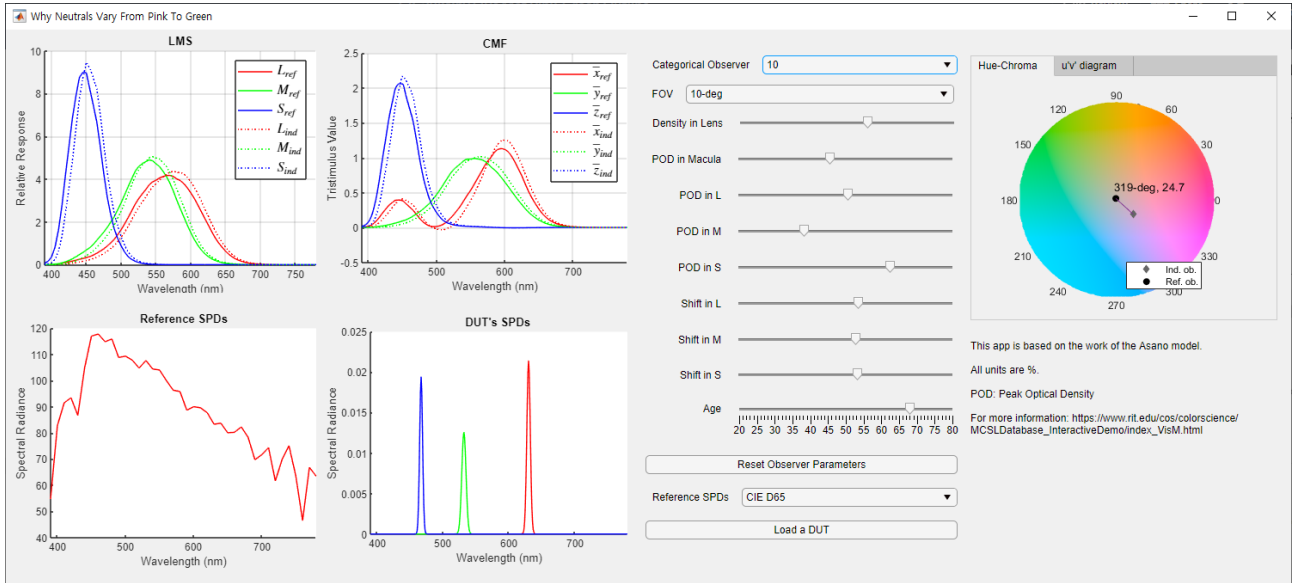
Figure 3: GUI implemented for the simulations.

Table 1: Specifications of physiological parameters and age used in the work and the 10-categorical observers. Note that all the values except for age are in numbers of standard deviation (σ), and the range values of the 8 physiological parameters in the first column are in percentage (%), which indicate an 1σ of each individual parameters.

		Group #1				Group #2			Group #3		Group #4
	1-SD (σ)	#2	#4	#7	#9	#1	#5	#6	#3	#8	#10
ine Age	20 ∼ 80	30	33	31	35	38	38	45	56	51	78
Lens	18.70	-1.23	-0.45	-1.82	-0.98	0.00	0.09	0.38	0.91	0.80	0.58
Macula	36.50	0.19	-1.19	0.99	-0.33	0.00	1.50	-0.97	-0.30	0.84	-0.44
PL	9.00	-1.23	0.65	0.81	-0.27	0.00	0.41	0.53	0.07	0.27	0.08
PM	9.00	-0.55	0.50	0.82	-0.78	0.00	1.78	1.29	-0.61	-0.97	-1.15
PS	7.40	1.03	0.03	-0.62	-1.34	0.00	-0.28	-0.60	-0.14	-0.01	1.26
SL	2.00	-0.05	-0.52	-0.31	0.17	0.00	0.57	-0.30	0.43	0.25	0.37
SM	1.50	0.22	-0.94	0.10	-0.39	0.00	-0.75	-0.85	0.34	0.06	0.28
SS	1.30	-0.61	0.04	0.61	-0.07	0.00	0.18	-0.05	0.55	0.10	0.33
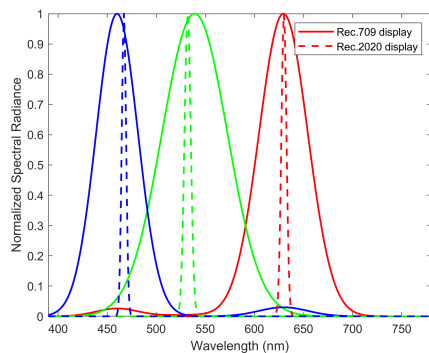
Figure 4: Spectral power distributions (SPDs) of two simulated display.

(a) On the narrow-band-primary display (ND) (b) On the broad-band-primary display (BD)

Figure 5: Color variations of the CIE D65 metamer for the CIE 2006 32-years-old 10° observer on the a*-b* plane of the CIELAB color space that the Asano's 10 categorical observers see on the two different displays.

lens density and age give the biggest impact on the inter-observer variability and pinkish-greenish variation.

Finally, the question posed in the title is answered by examining the interaction between the SPDs of the primary stimuli and changes in cone fundamentals with age or lens density, as illustrated in Figure 9. When lens density / age increases, the response of the S and L cones increase together for the blue and red primaries, while the response of the M cones is essentially unchanged. This would generally represent a shift toward the pinkish perceptions. The opposite occurs when lens density/age
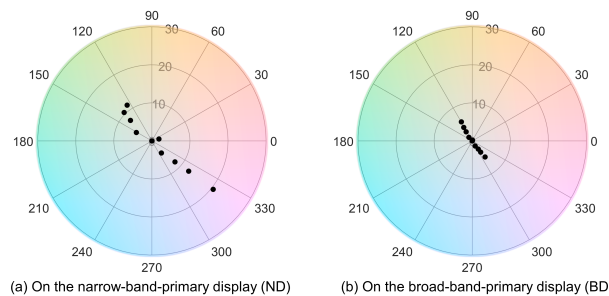
decreases, producing shifts toward green perceptions. Thus it is the interaction between the SPDs of display primaries and the most significant changes in cone fundamentals across individual observers that produce the commonly observed pinkish-greenish shifts.

Seeking an observer who sees yellowish-bluish

The final simulation was run to investigate whether people can perceive a yellowish-bluish variation of the white metamer. The idea to generate observers to see a yellowish-bluish variation
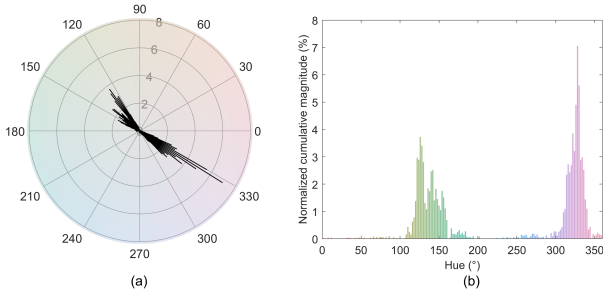
Figure 6: Normalized cumulative magnitudes from the simulation of all the possible primary combinations on the (a) hue-chroma plot and (b) bar chart.
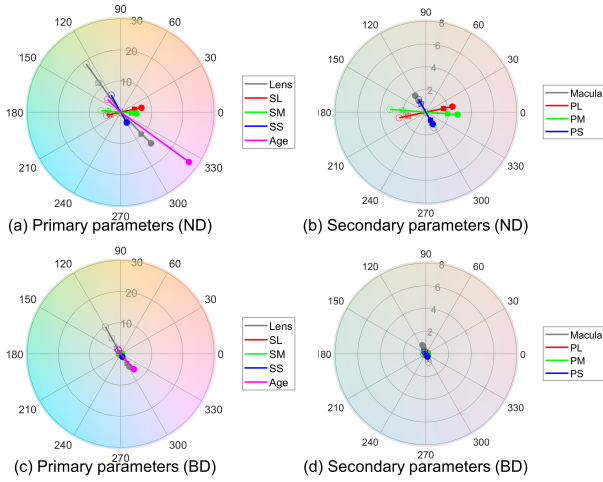

(a) Primary parameters (ND)

(b) Secondary parameters (ND)

(c) Primary parameters (BD)

(d) Secondary parameters (BD)

Figure 7: Effects of the 8 physiological parameters and age on the purple(pink)-green variation. The circles, diamonds, and pentagons, in turn, represent that the values of the physiological parameters are 3, 2, and 1 σ distance from the means. The filled shapes indicate positive standard deviations while the empty shapes indicate negative standard deviations. Note that changes in all the physiological parameters except for SL, SM, PL, and PM result in the pinkish-greenish variation. On the other hand, the four secondary parameters likely cause other color variations, such as reddish-cyanish variation.

was based on the observation depicted in Figure 7 that both L and M cone modifications could lead to the reddish-cyanish variation. In contrast, the cone alterations of the other parameters result in the pinkish-greenish variation. Thus, a yellowish-bluish variation could be created by mixing the two different color variations. In order for this, four parameters that arise the reddish-cyanish variation: Peak optical density in L, Peak optical density in S, Peak wavelength shift in L, and Peak wavelength shift in S, and one parameter that yields the pinkish-greenish variation: Lens density were selected, although lens density could be replaced with other parameters which cause the pinkish-greenish variation. To represent a distinguishable yellowish-bluish variation, somewhat extreme values for the parameters were determined as described in Table 2. Note that all the values in Table 2 are n-σ distance from the means, and two different observers were generated for each color variation (yellowish or bluish).

Figure 10 and 11 represent the cone fundamentals of these observers and the reference observer and what colors these observers can perceive. There are several points noteworthy. First, the cone modifications for the selected physiological parameters solely impact on the relative responses of only L and S cones to the display primaries. In particular, the cone modification for the Y 3-SD observer induces that the response of L cones to the red primary increases while that of S cones to the blue primary

decreases. However, the response of S cones barely changes. Therefore, this modification would cause a shift toward the yellowish perceptions. On the other hand, the cone modification for the B 3-SD observer lead to the responses of L and S cones in the opposite way, which would result in the bluish perceptions.

Second, the Y 3-SD and B 3-SD observers clearly perceive yellowish and bluish variations, respectively, on the narrow-band primary display but not on the broad-band primary display. Also, the 1-SD observers seem to be able to recognize yellowish and bluish variations, respectively, on the narrow-band primary display but may not be significant. This result indicates that the observer-variability would heavily depend on the primaries of displays or color stimuli, as mentioned above. Furthermore, +3 or -3 indicates that the value of the parameter is a 3σ away either towards a positive or negative direction from the mean. By the definition of standard deviation in a normal distribution, those values mean that the value is what only 0.15% of the color-normal populations could have for each parameter. Therefore, it implies that the 3-SD observers are not likely color-normal observers in terms of probability. Besides, the significant L and S cone shifts suggest that these observers would be anomalous trichromats.
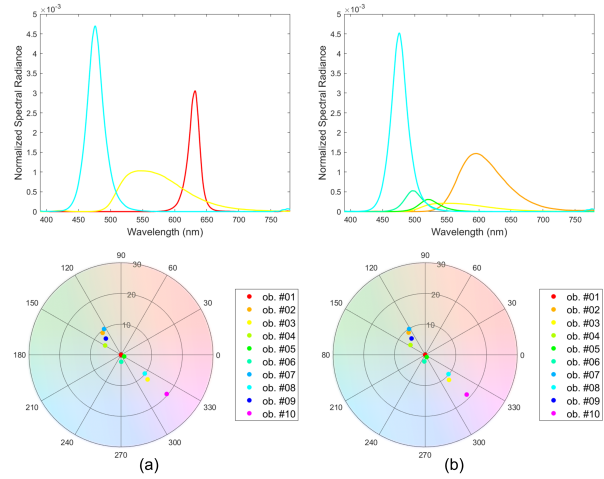

Figure 8: The pinkish-greenish variation on two different simulated displays, (a) a 3-primary combination and (b) a 5-primary combination. Note the observers clustered as well.

Table 2: Values of 8 physiological parameters in the σ distance for a yellowish-bluish variation. Note that Y n-SD obs are for a yellowish variation while B n-SD obs are for a bluish variation.

	Y 1-SD ob.	Y 3-SD ob.	B 1-SD ob.	B 3-SD ob.
Lens	-0.33	-1	+0.33	+1
Macula	0	0	0	0
PL	+1	+3	-1	-3
PM	0	0	0	0
PS	-1	-3	+1	+3
SL	+1	+3	-1	-3
SM	0	0	0	0
SS	-1	-3	+1	+3

Conclusion

In this paper, a peculiar question, "Why do observer metamers of white usually appear pinkish or greenish?", triggered by a visual demonstration, is addressed based on simulations. The simulation results indicate that lens density and age
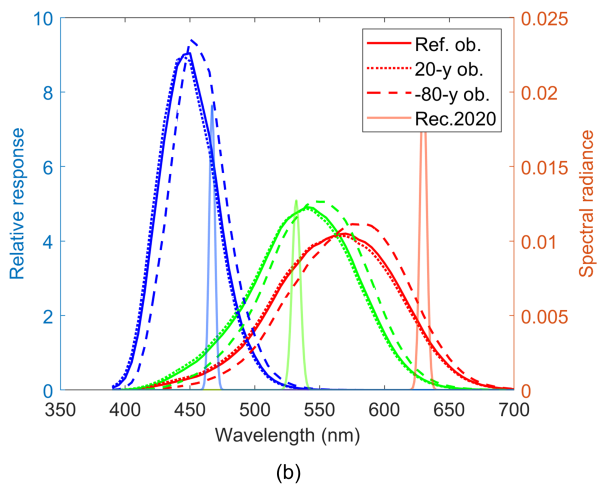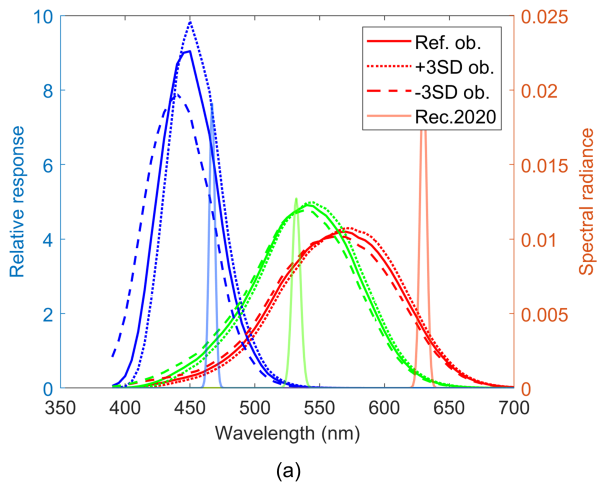
(a)

(b)

Figure 9: Cone fundamentals with the narrow-band primary display (Rec.2020) superimposed. (a): Three observers: the reference 10° observer, an observer with a lens density of $+3\sigma$, an observer with a lens density of -3σ. (b): Three observers: the reference 10° observer (32-y), an observer in his/her 20s, an observer in his/her 80s.
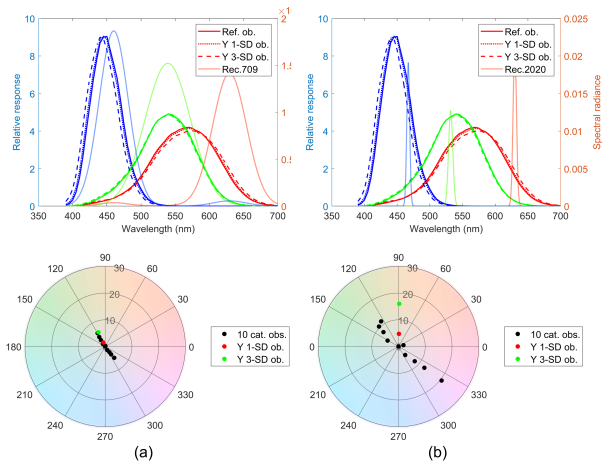

Figure 10: Cone fundamentals for a yellowish variation on the broad-band primary display (a) and narrow-band primary display (b). See Table 2 for the values used to create the observers and SD means σ.
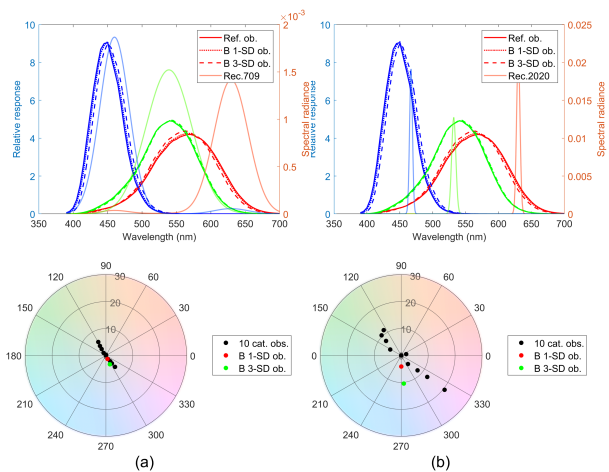

Figure 11: Cone fundamentals for a bluish variation on the broad-band primary display (a) and narrow-band primary display (b). See Table 2 for the values used to create the observers and SD means σ.

are the two biggest effects on the pinkish-greenish variation. Importantly, it was found that the pinkish-greenish variation is a result of the interaction between these two most prominent effects and color stimuli primaries. Also, an extra simulation revealed that the possibility of perceiving yellowish-bluish variations would be less likely in a color normal population. However, it should also be noted that all these simulations indicate these variations have strongly to do with the primary selection of color stimuli as well as the physiological variation of observers.

An interactive demonstration to help understand what this paper describes can be found: http://www.rit-mcsl.org/Research/WhyNeutralsVaryFromPinkToGreen/

Acknowledgments

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