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Contrast Adaptation and Wide-Gamut Light Sources

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Abstract

Illuminants vary not only in their mean chromaticity, but also in the range of colors they produce. For example, new high-gamut LED illuminants can expand the saturation of reds and greens by ~30% compared to natural illuminants. We examined how the visual system might adapt to the greater color gamut produced by these illuminants. Stimuli were colors shown on a monitor that simulated surfaces (Munsell spectra) illuminated by a broad (Planckian) or narrow (3-primary LED) illuminant with the same color temperature (2724 or 4000 K). Observers adapted to the simulated surfaces under each illuminant, shown either as a random temporal sequence in uniform fields or in random spatial arrangements in Mondrians. Both illuminants induced strong contrast adaptation. However, simultaneous matches between the two illuminants required significantly higher contrast along the reddish-greenish axis for the LED adaptation, consistent with a sensitivity loss induced by adaptation to the higher red-green contrast created by the LED illuminant. These results suggest that commonly available light sources may significantly alter the states of contrast adaptation in the visual system, and this contrast adaptation is important for understanding the perceptual consequences of both short and long-term exposure to wide-gamut illuminants.

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Contrast Adaptation and Wide-Gamut Light Sources

An emerging revolution in the illumination and display industry is the use of narrow-band light-emitting diodes (LEDs) to increase the gamut of colors [1]. These wide color gamut technologies have been heavily marketed as producing a richer color experience. For example, new wide-gamut LED illuminants can expand the saturation of reds and greens by roughly 30% relative to natural illumination [2]. Despite the prevalence of this new technology, the visual consequences of exposure to these displays remain poorly understood.

The visual system adapts over both short and long timescales to stimuli in the observer's environment, and this adaptation has profound effects on both visual sensitivity and appearance [3-5]. Adaptation to color occurs at multiple sites in the visual pathway and adjusts to distinct aspects of the stimulus. Light and chromatic adaptation begins in the receptors and adjusts to the time-averaged luminance and chromaticity in the scene [6-8]. Contrast adaptation reflects adjustments to the variation in color around the average, and for chromatic contrast is thought to occur primarily at cortical levels [9]. Both forms of adaptation continuously regulate color appearance and have been shown to induce distinct changes to color appearance [10-14]. Moreover, both are likely to play a prominent role in calibrating color vision in natural viewing [11,15]. For example, differences in the color gamuts of lush and arid scenes [11], or seasonal changes in the same environment [16,17], are sufficient to induce different states of contrast adaptation and consequent changes in color perception. Contrast adaptation effects are also manifest in the changes that are perceived in the “colorfulness” of indoor environments under different lighting contexts [18,19].

Here, we explored the consequences of this adaptation for the large contrast changes introduced by the modern wide gamut luminaires. Specifically, we explored how the visual system might be adapted to changes in the color distributions induced by these illuminants, and how this adaptation might shape how we perceive color.

To test this, we adapted observers to colors shown on a monitor that simulated the chromaticities that would be generated by the same set of surfaces viewed under natural or LED illuminants, and then had them match the colors across the different adaptation states. Our results suggest that adaptation to the higher color contrasts produced by wide gamut sources reduces the sensitivity of the visual system to chromatic contrast, relative to natural lighting. These effects are important for understanding the potential short and long-term impacts of high-gamut lighting on human color perception.

Methods

Participants

Observers included 11 undergraduate and graduate students. Different subsets of observers were tested for different conditions, as detailed below. All observers had normal or corrected-to-normal visual acuity, and normal color vision, as assessed by the Cambridge Colour Test. Observers participated with informed consent and all procedures followed protocols approved by the University of Nevada, Reno’s Institutional Review Board.

Apparatus and Stimuli

The stimuli were presented on an NEC MultiSync FP2141SB CRT monitor controlled by a Cambridge Research Systems ViSaGe board, which allows colors to be specified with high (14-bit) resolution. The monitor was calibrated using a Photo Research PR 655 spectroradiometer, with gun outputs linearized through lookup tables.

The monitor was used to simulate the colors from naturalistic surfaces viewed under different illuminants in the following steps. First, we constructed broadband and wide-gamut illuminants that were approximately matched in color temperature. Figure 1 shows the spectral power distributions of the illuminants used. The top panel shows the standard (Planckian) and LED illuminants at 4000K, and the bottom graph shows the standard (Planckian) and LED illuminants at 2724K. Second, we simulated a set of surfaces by constructing reflectance functions from the first three basis functions characterizing the Munsell reflectance spectra [20], which have broad and smoothly varying spectra characteristic of natural surfaces [21]. The calculation was based on the matrix relating the basis functions under the Planckian illuminant to the L, M, and S cone excitations:

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} W_{L1} & W_{L2} & W_{L3} \\ W_{M1} & W_{M2} & W_{M3} \\ W_{S1} & W_{S2} & W_{S3} \end{bmatrix} \begin{bmatrix} I_P R_1 \\ I_P R_2 \\ I_P R_3 \end{bmatrix} \qquad \textbf{(1)}$$

or

$$\mathbf{c = Ws} \qquad \textbf{(2)}$$

Here L, M, and S are the cone responses (c), Ip is the illuminant, R1, R2, R3 are the basis functions for the reflectances, and s is the resulting color signal. This allowed us to specify the surfaces in terms of their cone excitations, and then derive the reflectances that would give rise to these cone responses by inverting the matrix:

$$s = W^{-1}c \text{ and } r = s/i$$

The cone values for the stimulus set were selected based on chromatic contrasts defined within the LvsM and SvsLM cone-opponent space of MacLeod-Boynton [22] and Derrington, Krauskopf and Lennie [23]. Our version of the space was related to the MacLeod-Boynton r,b coordinates by the following equations:

$$\begin{gathered} \text{LvsM} = (r-0.6568) * 1955 \\ \text{SvsLM} = (b-0.01825) * 5533 \end{gathered}$$

where the gray point was set at the chromaticity of Illiminant C and the scaling factors roughly equated contrasts along the two axes [12]. The mean luminance of the stimuli and the background was 20 c/m^2. The stimuli were chosen to define a uniform distribution of stimuli in the LvsM and and SvsLM plane, assuming complete chromatic adaptation to the mean chromaticity of the Planckian illuminant (modeled as independent gain changes in the cones so that after adaptation the mean had zero color contrast or appeared gray [10]). We then simulated the distribution of color signals for the same set of surfaces under the LED illuminant.

Figure 2 shows an example of the resulting stimuli. The ellipse on the lower left represents the pre-adapt LvsM and SvsLM coordinates for the surfaces under the

Planckian illuminant, and the circle on the upper left represents the predicted coordinates after complete chromatic adaptation to the illuminant, so that the stimuli are now centered on the gray point and form a circle of equal contrast. The ellipse on the lower right represents the pre-adapt LvsM and SvsLM coordinates when the surfaces are instead seen under the LED illuminant, while the upper right again shows the predicted chromaticities after assuming complete chromatic adaptation to the mean. Note that the chromaticities under the LED are stretched along the LvsM axis, forming more elliptical contours, and that this expansion is preserved after adaptation to the average illuminant color.

Procedure

In the experiments, we examined the consequences of adaptation to the difference in LvsM contrast for the two illuminants, in 4 conditions that varied either the temporal or spatiotemporal contrast of the adapting stimuli. For all conditions observers viewed the display binocularly at a distance of 150 cm, in an otherwise dark room, and used a keypad to record their responses.

Experiment 1: Adaptation to a Single Illuminant: The first experiment examined the absolute magnitude of chromatic and contrast adaptation to the color gamuts for each illuminant, by using an asymmetric matching task to compare color appearance between fields under adaptation to the illuminant vs. a zero-contrast gray field. The stimuli were shown in two 4-deg fields above and below fixation. Observers adapted for 3 minutes to a random sequence of the chromaticities of either illuminant (Planckian or LED 4000 K) in the top field. The adapt distribution formed a set of 16 chromaticities centered on the illuminant mean and with a fixed contrast of 40. Again, these were defined so that the set would form a uniform circle if there were complete chromatic adaptation such that the mean of the Planckian illuminant appeared gray. During adaptation observers viewed a random sequence of stimuli from the distribution, with a new color sampled every 200 ms. This simulates the pattern of temporal variation that might result from randomly sampling a scene with successive eye movements. A test stimulus was then presented for 500 ms in the same field, and observers matched the appearance of the test stimulus by using a keypad to adjust the hue angle and contrast of a comparison stimulus shown simultaneous with the test in the gray adapting field. The test stimulus was shown interleaved with 4-sec readaptation to the gray field until the observer completed the match, after which the program presented the next test stimulus. The test stimuli consisted of 16 hues at steps of 22.5 deg, and a contrast of 40 relative to the mean of the illuminant. Note that the test stimuli had the same chromaticity for the two adapting conditions (i.e., they were not the chromaticities of the simulated surfaces). This was to allow us to use identical tests to probe differential adaptation to the different chromaticities produced by the two illuminants. To isolate the effects of chromatic and contrast adaptation, matches were also made after adapting to the steady uniform mean chromaticity of the illuminant rather than the individual samples from the reflectance gamut. For each adapting condition, matches were made to each test 4 times in counterbalanced order. Results reported are based on the means of the matches.

Experiment 2: Dual Adaptation to Both Illuminants: To gain a more sensitive comparison of the *relative* adaptation induced by the broadband and wide gamut illuminants, observers simultaneously adapted for 3 minutes to a random sequence of the same set of surfaces under both the Planckian and LED illuminants, shown in the top and bottom field, respectively. The adapt and test stimuli and sequence were the same as in the preceding experiment. However, in this case the adapting gamuts and test stimuli were shown in both fields. Specifically, during the adaptation, the same random sequence of surfaces was shown in both fields but under the two different illuminants. During testing, observers matched the appearance across the two fields by adjusting the relative hue and contrast of the test stimuli shown in both fields. The test pair were yoked so that increasing the test contrast in the top field reduced it in the bottom field, or vice-versa.

Experiment 3: Adaptation Effects on Color Contrast Thresholds: We also evaluated the changes in the detection thresholds for LvsM chromatic contrasts for the adapting gamuts. The adapt stimuli and sequence were the same as those in Experiments 1 and 2. However, in this case the adapt stimuli were displayed in a single, centrally fixated 4 deg field, which was divided by narrow black lines into 4 1-deg quadrants. On each trial the test was displayed randomly in one of the quadrants, and staircase was used to estimate the detection thresholds. Thresholds were measured for either an increment or decrement along the LvsM axis, before or after adapting to the two illuminants. For each test angle, threshold measurements were made 4 times in counterbalanced order with 15 reversals per staircase.

Experiment 4: Adaptation to Color Contrast in Spatial Patterns: The final experiment was designed to generalize the preceding conditions to more naturalistic viewing conditions, by adapting to spatially varying color distributions that are more characteristic of actual scenes. In this case the stimuli were again shown in two 4-deg fields, now on the left and right of a fixation cross but were filled with Mondrians composed of random overlapping rectangles. The left and right side had the same spatial pattern but were mirrored to aid comparing them. The color coordinates of the rectangles were drawn from the color distributions of the illuminants and were also now varied in luminance. As before, observers adapted to random sequences of the colors shown in the Mondrians every 200 ms. The test stimuli had a fixed SvsLM contrast and observers varied relative magnitude of LvsM contrast to match the perceived contrast. The test pair were yoked so that increasing the test contrast in the top field reduced it in the bottom field, or vice-versa. Importantly, for these conditions the test stimuli had the same overall contrast as the adapting stimuli, and thus also directly assessed the changes in the perceived contrast of the adapting gamut itself. To fully assess these contrast changes, we measured the matches for 4 adapting conditions: 1): Pre-adapt: adaptation was to a gray field in both sides. Thus, the matches for the test Mondrians should occur when the two sides had the same physical contrasts and assessed the ability to correctly set the matches. 2) Planckian vs. LED: observers adapted to the set of Mondrians simulated under the Planckian illuminant on the left side and the set of Mondrians simulated under the LED illuminant on the right side; 3) Grayscale vs. Wide gamut: this condition compared adaptation between the color gamut and the grayscale Mondrian to examine the degree of chromatic adaptation when controlling for the luminance contrasts in the stimuli; and 4) S contrast vs. Wide gamut. In this condition one adapting field displayed the illuminant gamut while in the other the LvsM contrast was set to zero so that the Mondrian only varied in SvsLM and luminance contrast. This was again tested to isolate the contribution of the LvsM contrast to the changes in perceived contrast. Observers made 20 matches for each condition.

Results

Experiment 1: Adaptation to a Single Illuminant

As noted, in the first case we assessed the magnitude of adaptation for the individual illuminants by comparing color appearance after adapting to each illuminant gamut vs. a uniform gray field. Figure 3 shows the predicted pattern of adaptation effects for either 4000K illuminant. The lower right ellipses show the coordinates of the test stimuli in the cone-opponent plane, which are centered on the yellowish mean chromaticity of the illuminant. The blue and red represent the Planckian and LED, respectfully. Chromatic adaptation to this mean should recenter the coordinates around the gray chromaticity of the background color. In addition, contrast adaptation should reduce the perceived contrast of the illuminant gamut, so that the matching stimuli have lower contrast than the test stimuli. Figure 4 plots the actual measurements of these effects for 3 observers tested. In this case, the illuminants had a color temperature of 4000K. The black stars represent the test stimuli (before adaptation). (Note these are centered on slightly different mean chromaticities because the calculated sources did not fully equate the means for this condition, though this negligibly impacts the measured effects.) The black symbols (square and diamond) represent the Planckian and LED match stimuli (after adaptation), respectively. The black dashed line represents the predictions for adaptation to only the mean. For all subjects, the matches show strong, but incomplete chromatic adaptation. That is, the matching coordinates are strongly shifted toward the neutral gray but have a residual bias in the mean. Both the broadband and wide-gamut illuminants also produced pronounced contrast adaptation. Specifically, the match contrasts for the adapting sequence are substantially lower than when adapted to the static illuminant mean. However, in this case the magnitude of contrast adaptation appears similar for the two illuminants. To assess this, we compared the magnitude of the LvsM matching contrasts relative to the sample mean for each observer. For all 3 observers, t-tests indicated that there was not a statistically significant difference in magnitude of matching contrasts for the Planckian illuminant vs. LED illuminant [$t(30) = .58$, $p = 0.56$; $t(30) = 1.21$, $p = 0.23$; $t(30) = .31$, $p = 0.75$, for the 3 observers]. Thus, while this experiment allowed us to assess the strong adaptation effects for both illuminants, it did not reveal clear differences between them.

Experiment 2: Dual Adaptation to Both Illuminants

To provide a more sensitive measure of differential adaptation to the two illuminants, we turned to the second study condition where both illuminant gamuts were shown simultaneously in the two fields, and then measured the differences in color appearance between the two fields. Unlike the preceding measurements, this condition cannot reveal the absolute changes in chromatic or contrast adaptation common to both gamuts but provides a more direct measure of any differences in the adaptation.

Figure 5 show the matches between adaptation to either illuminant at 2724K for each of the 7 observers tested. The black line represents the Planckian matches and the black star represents the LED matches. In this case, the matches required consistently higher contrast along the LM axis for the field adapted to the LED illuminant. This was again assessed by comparing the LvsM contrasts relative to the sample mean for the two. A paired-samples t-test on the mean across observers indicated that contrasts along the LvsM axis were on average 1.24 times higher for the LED illuminant than for the Planckian illuminant, a difference that was highly significant, $t(15) = -5.72$, $p = 0.00004$.

The LvsM contrast in the matches was also significantly higher for the LED adaptation for each of the 7 individual observers, *t*(15) >= -3.61, *p* <= .002. The contrast differences are consistent with a sensitivity loss induced by selective adaptation to the stronger red-green contrast created by the LED illuminant.

Experiment 3: Adaptation Effects on Color Contrast Thresholds

The preceding results showed that adaptation to the LED gamut reduced the perceived contrast of the suprathreshold stimuli relative to the broadband illuminant. We next evaluated whether it also showed up as a difference in detection thresholds for the LvsM contrasts. Figure 6 compares the chromatic contrast thresholds along the LvsM axis for both adaptation conditions. A three-way ANOVA was run to examine the effect of adaptation (mean vs. gamut), lighting (Planckian vs. LED), and direction (0 vs. 180) on chromatic contrast thresholds. There was a significant main effect of adaptation on thresholds, *F*(1,7) = 55, *p* = 0.001, but no significant main effect of lighting on chromatic contrast thresholds, *F*(1,7) = 0.35, *p* = 0.58 or direction on chromatic contrast thresholds, *F*(1,7) = 0.05, *p* = 0.83. Across all observers, adaptation to either illuminant gamut produced an elevation in the contrast thresholds compared to the thresholds after adapting to the illuminant mean. However, like the first experiment, in this case the difference between the chromatic contrast thresholds for the Planckian and LED illuminants was not significant.

Experiment 4: Adaptation to Color Contrast in Spatial Patterns

The final set of experiments were again designed to confirm the contrast adaptation effects for spatially varying stimuli, by presenting the adapting gamuts in Mondrian displays rather than uniform fields. The task in this case was to match the perceive LvsM contrast in the Mondrians after adapting to the illuminant gamuts vs. control gamuts. Figure 7 shows the contrast ratio between two adapting fields for each condition. In this experiment, 5 observers were tested, and the bars plot the mean settings + 1 sd. The height of the bars shows the deviation from a physical match (a ratio of 1). As expected, the pre-adapt conditions do not significantly differ from a physical match. However, for the remaining conditions adaptation to the higher LvsM contrast reduced the perceived contrast in the Mondrians. There was a statistically significant difference between conditions as determined by a one-way ANOVA, *F*(3,16) = 9.22, *p* = .0008. A Bonferroni post hoc test revealed that matches required significantly higher contrasts for the Mondrians after adaptation to the s contrast (M = 44.13 , SD = 317.87) and wide-gamut (M = 61.17, SD = 544.83) conditions compared to the pre-adapt conditions. Most importantly, matches required significantly higher contrasts for the Mondrians with the wide-gamut vs. broadband adaptation, *t*(15) = -2.91, *p* = .01. These results thus replicate the differential contrast adaptation effects for the two illuminant gamuts found with the uniform fields. Moreover, they also extend these results by illustrating the effects of adaptation on the perceived contrast of the adapting gamut again showing reduced sensitivity to chromatic contrast after exposure to the wide-gamut illuminant.

Discussion

In this study, we systematically investigated how the visual system might adapt to short-term changes in the color environment induced by the emerging changes in artificial lighting that boost the chroma most humans are exposed to. Consistent with previous studies our results show that states of chromatic adaptation remain similar after exposure to artificial or broadband illuminants that have the mean chromaticity but produce different gamuts [10,14]. However, the side-by-side comparisons (experiments 2 and 4) reveal significant differences in the amount of contrast adaptation that the different illuminants produce. Specifically, the wider gamut generated by the LED lighting led to significantly greater adaptation. This alteration in contrast adaptation is largely specific to the LvsM axis along which the gamuts differed, consistent with the selectivity that has been observed previously in color contrast adaptation [12,19]. While the pattern of adaptation effects we measure are thus predictable, what is important and shown here is that they can be manifest for the changes in color gamut introduced by increasingly common light sources.

What are the short and long-term perceptual consequences of this selective adaptation to wide gamut artificial illuminants? For short-term exposures, contrast adaptation effects tend to build up exponentially during adaptation, and similarly can decay exponentially after the adapting stimulus is removed [24]. However, some color aftereffects can last a very long time [25-27], including McCollough effects which are effectively permanent until actively extinguished by de-adaptation [28]. There is also evidence that repeated exposures can change the dynamics of adaptation [29]. Similar evidence for multiple time scales and dynamics have also been found for both luminance [30,31] and chromatic [32,33] contrast adaptation. The variety of these effects leave open the possibility that routine exposure to the contrast changes produced by wide-gamut light sources could introduce both short and long-term changes in color appearance. It will be important in future studies to assess the time course of this adaptation for more natural viewing conditions.

It will also be important to explore the magnitude of these adaptation effects under more natural viewing conditions. Our studies used highly controlled stimulus exposures that clearly differ from the patterns of exposure and sampling that would result with natural scenes. However, color contrast adaptation effects are also pronounced for natural color gamuts [11], and similarly luminance contrast adaptation is strong in response to actual images [34,35].

An important property of adaptation is that it tends to normalize visual coding [2]. In the case of color this includes shifting appearance so that the average color appears more neutral (gray) and the range of contrasts along different color and luminance axes appear more balanced. This predicts that adaptation to wide-gamut lighting should tend over time to desaturate the colors under that lighting so that they start to appear more natural. In turn this could lead actual natural gamuts appearing unnatural or reduced in contrast. Further characterization of these effects and the extent to which they occur in real environments will be important for assessing the long-term consequences of changes in artificial illumination sources.

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Figures

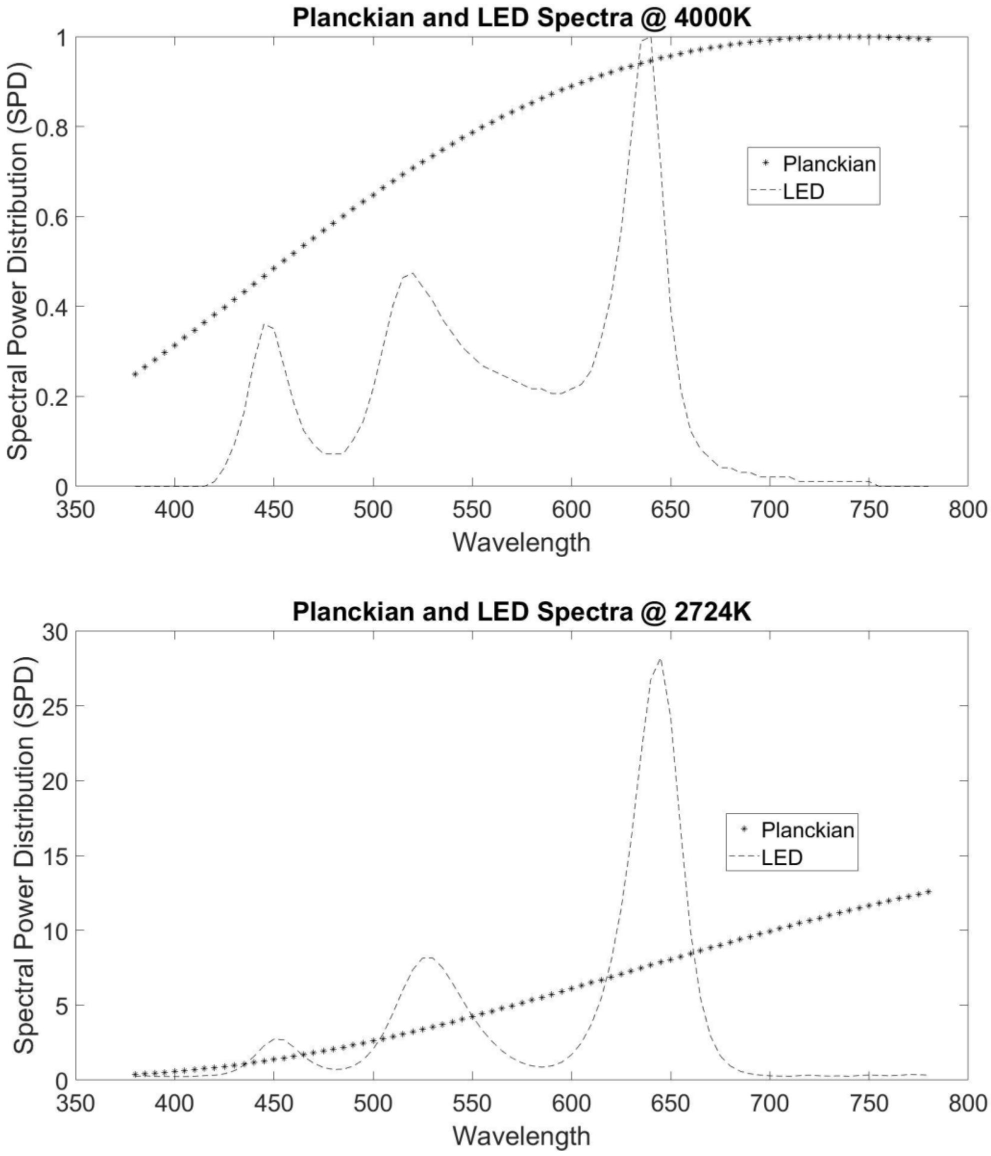

Figure 1. The spectral power distributions for the experimental illuminants. Each graph shows the spectral power distribution of the Planckian and LED illuminants at 4000K (top) and 2724K (bottom).

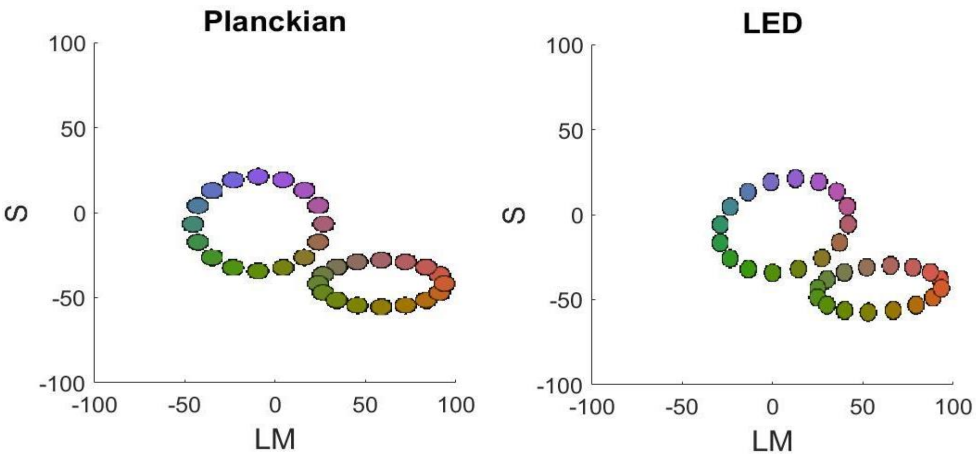

Figure 2. Predicted colors for the stimulus set under each illuminant before (lower ellipses) and after (upper ellipses) adaptation to the mean chromaticity.

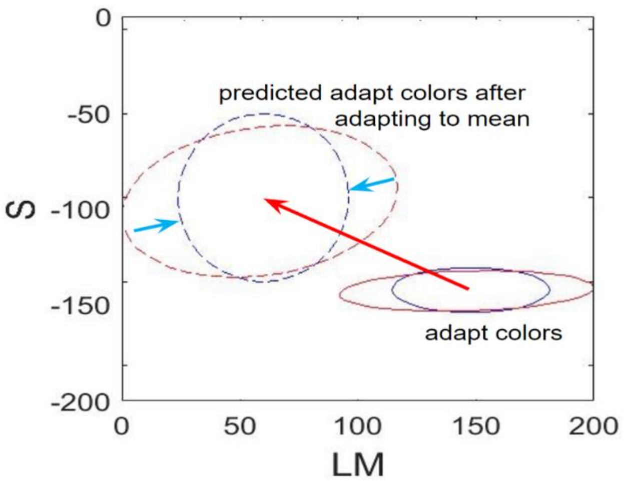

Figure 3. Predicted colors after adaptation to the mean for either 4000K illuminant. The blue and red ellipses (bottom right) represent the Planckian and LED test stimuli, respectfully. The blue and red circles (top left) represent the Planckian and LED colors after adaptation to the mean color of each illuminant.

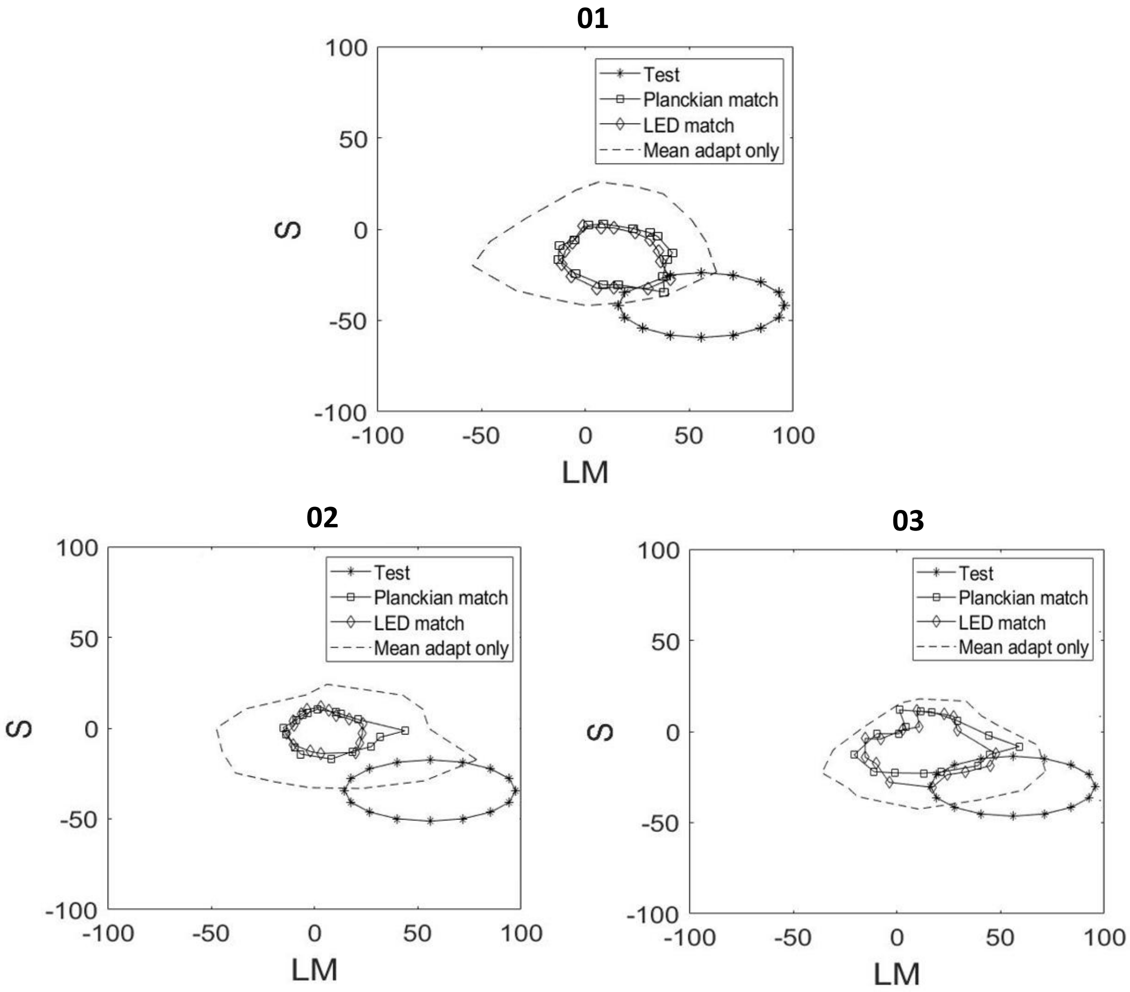

Figure 4. Matches after adaptation to either 4000K illuminant. The black symbols (stars) represent the test stimuli. The black symbols (squares and diamonds) represent the Planckian and LED matches, respectfully. The black dashed line represents the predictions after adaptation to only the mean.

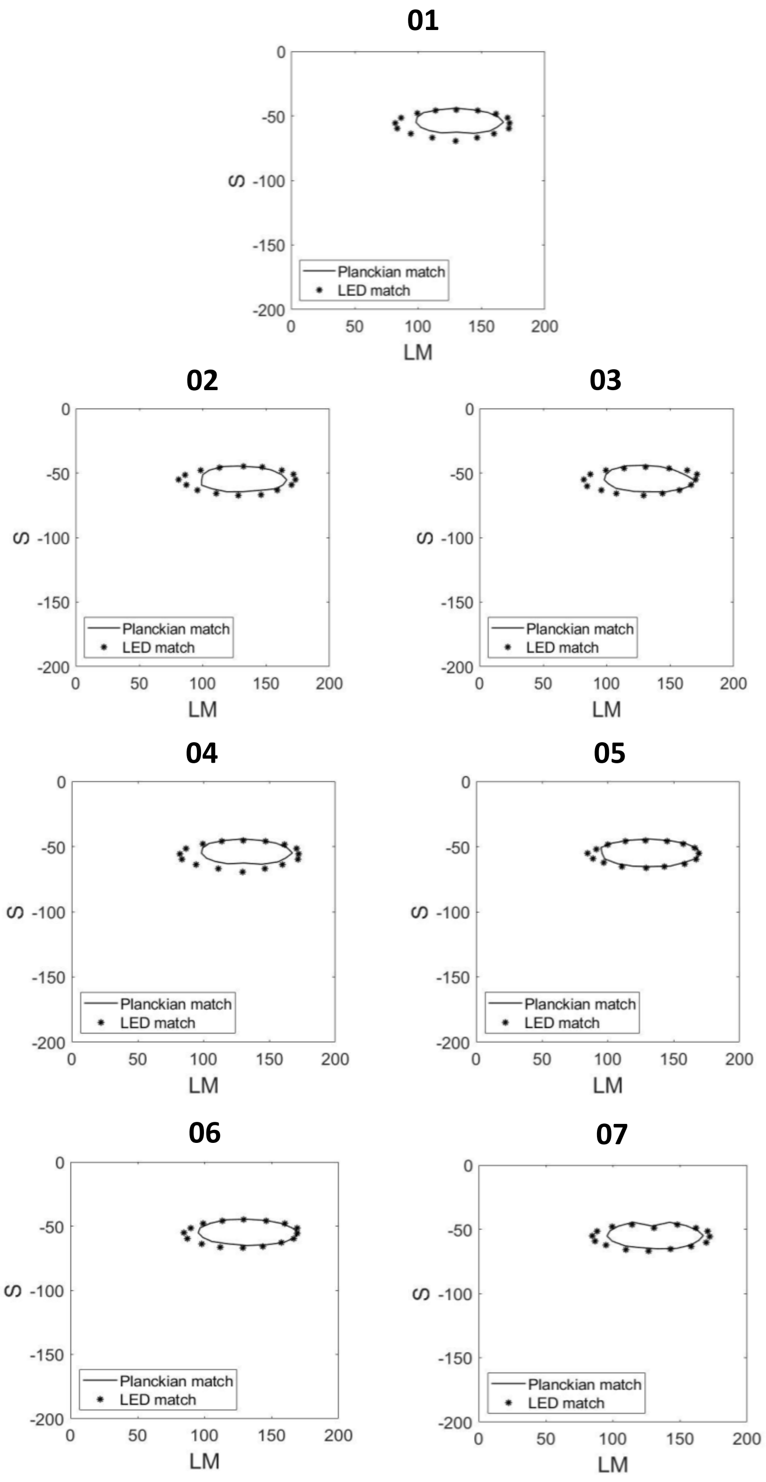

Figure 5. Matches after dual adaptation to either illuminant at 2724K for 7 observers. The black stars represent the Planckian matches and the black line represents the LED matches. For all observers, the matches required significantly higher contrast along the LM axis for the field adapted to the LED illuminant.

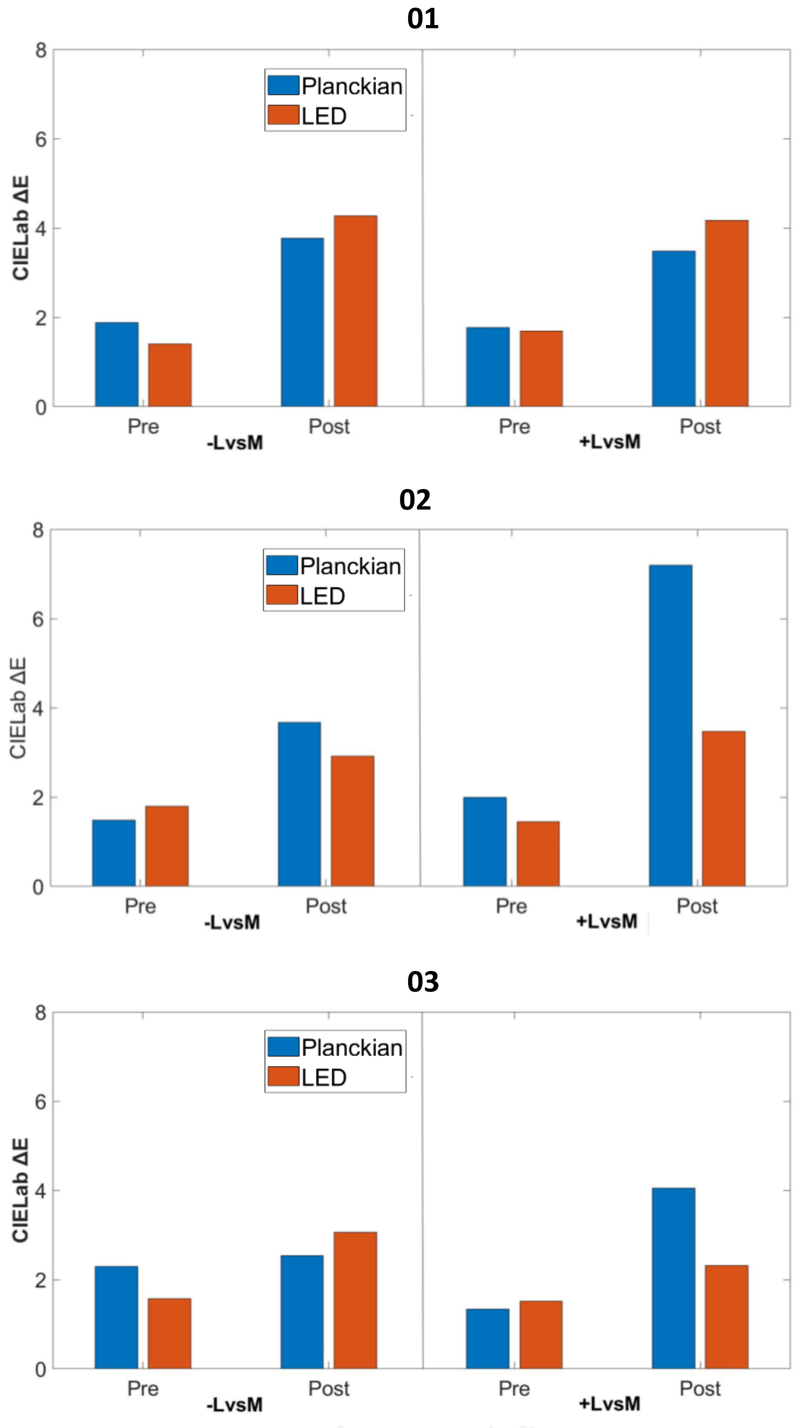

Figure 6. Average chromatic contrast threshold settings for the 3 observers.

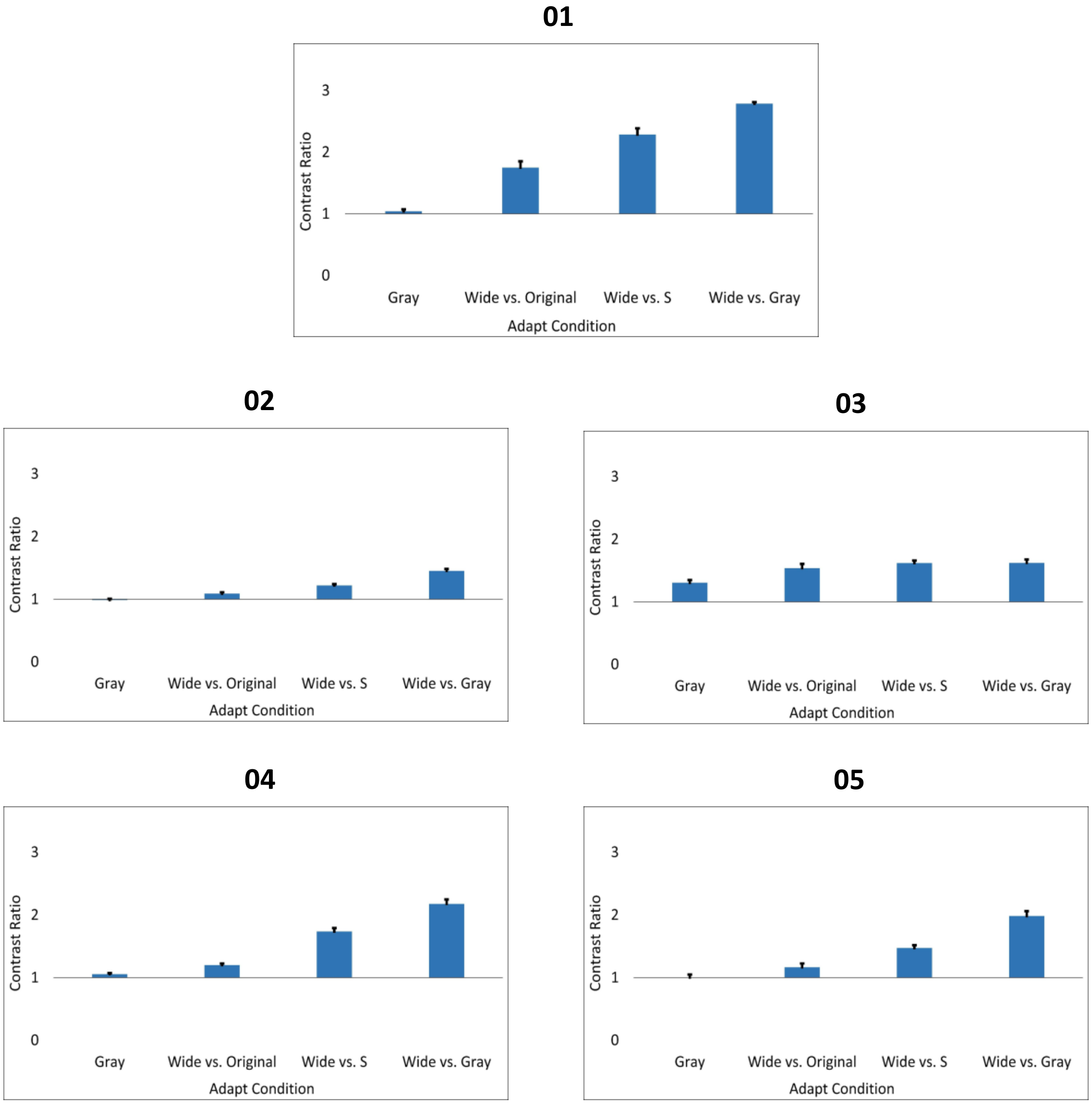

Figure 7. Contrast ratio between the two adapting fields shown for the 5 observers.