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Effect of Stimulus Luminance and Adapting Luminance on Viewing Mode and Display White Appearance

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Abstract

Past studies found that displays and surface colors needed very different chromaticities to produce white appearance and attributed such a difference to the different degrees of chromatic adaptation caused by the viewing media. This study aimed to test whether the different chromaticities for producing white appearance were caused by viewing medium or viewing mode. Observers were asked to adjust the stimuli at different luminance levels on an iPad display until they appeared white under different adapting conditions (i.e., adapting luminance and adapting chromaticities). The results clearly suggested that the different chromaticities for producing white appearance were due to the viewing mode of the stimulus, which was jointly affected by the stimulus luminance and adapting luminance, rather than viewing medium. It also suggested the necessity to develop a comprehensive color appearance model and uniform color space for self-luminous stimuli, which will be important to the color reproduction in HDR imaging systems.

Introduction

White appearance is critically important to both imaging and surface color industries, as it is always associated with product quality. On the other hand, white appearance is of great interest to the researchers working on color appearance models and chromatic adaptation, since white is believed to be the only unambiguous memory color [1]. The researchers asked the observers to rate the white appearance of the stimuli or to adjust the stimuli until they appeared white.

For surface colors, the chromaticities of the adapting background were found to have a significant effect on the white appearance of stimuli. The chromaticities of the whitest stimulus were generally around those of the adapting background [2,3]. On the contrary, the effect of the adapting background chromaticities was found much smaller for the stimuli produced on a self-luminous display. The chromaticities of the whitest stimulus under different adapting background chromaticities were commonly found to converge towards certain chromaticities. Though the converging chromaticities varied from study to study, they were generally between 6500 and 9000 K [2,4,5].

Such a difference of the chromaticities for producing the whitest appearance was commonly attributed to the different degrees of chromatic adaptation caused by the viewing media. It is believed that both sensory and cognitive mechanisms of the chromatic adaptation are active for perceiving surface colors, but only sensor mechanism is active for perceiving stimuli on displays [2,6]. Thus, displays are thought to cause an incomplete chromatic adaptation, making the adapting background chromaticities have smaller effect on the color appearance of stimuli. Zhai and Luo specifically investigated the difference of the white appearance between a display and a surface color under a same adapting condition (i.e., adapting luminance and adapting chromaticities) and surround condition and introduced different degrees of chromatic adaptation factor D for different viewing media (i.e., displays and surface colors) [2].

The effect of viewing media, however, may be confounded with the viewing mode, since displays typically produce self-luminous stimuli and surface colors produce surface color stimuli. As found by Evan, there exists a zero gray point (G_0). A stimulus with a luminance below G_0 appears as a surface color; while a stimulus with a luminance above G_0 appears self-luminous [7].

This article reports a psychophysical study for matching stimulus with the whitest appearance on an iPad display under different adapting backgrounds. We purposely used an iPad display to produce the stimuli with a wide range of luminance (i.e., from 100 to 350 cd/m^2) under two levels of adapting luminance (i.e., Y_W = 130 and 900 cd/m^2), so that the stimuli may be perceived in the self-luminous mode under the low adapting luminance level but in the surface mode under the high adapting luminance level. Coupled with the fact that the observers were well aware of the media of iPad display, the effect of viewing media on white appearance and degree of chromatic adaptation can be completely isolated.

Methods

Apparatus, stimuli, and adapting backgrounds

The experiment was carried out using a viewing booth, with dimensions of 60 cm × 60 cm × 60 cm and the interiors being painted with Munsell N7 spectrally neutral painting. An 9.7-inch iPad was placed on a 45° viewing table at the center of the viewing booth to produce stimuli, with a Munsell N8 color sheet being placed above it. A 3 cm × 3 cm square was cut at the center of the Munsell sheet, with eight NCS color samples (3 cm × 3 cm) being placed around it. A chin rest was fixed in front of the viewing booth, so that the viewing booth covered the observers' entire field of view (FOV) and the observers perpendicularly viewed the stimulus on the display with an FOV around 5°. Figure 1 shows the setup of the experiment.

The iPad display was characterized using the GOG model with the CIE 1964 10° Color Matching Functions (CMFs). An APP was developed, so that the chromaticities (u',v') of the display can be adjusted remotely with a step of 0.001 along the u' and v' axis using the four arrow keys on a keyboard, with Y being kept constant.

The observers made the adjustments at six levels of the display luminance (i.e., Y = 100, 150, 200, 250, 300, and 350 cd/m^2).

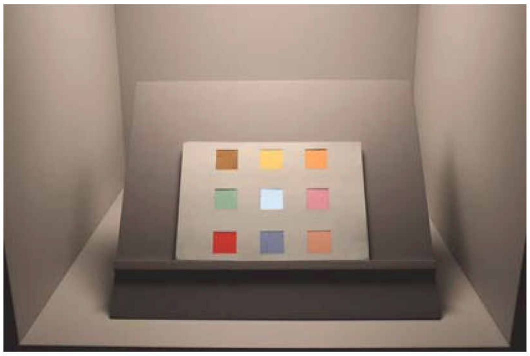

Figure 1 Photograph of the experiment setup. The center patch, with dimensions of 3 cm × 3 cm, was produced by a 9.7-inch iPad, subtending around 5° field of view.

Part 1: Low adapting luminance

A 11-channel spectrally tunable LED device was placed above the viewing booth to produce four illuminants (i.e., CCT of 2700, 3500, 5000, and 6500 K) with a D_{uv} of 0.000 around 130 cd/m^2, which were calibrated using a JETI specbos 1511UV spectroradiometer. Table 1 summarizes the colorimetric characteristics of the illuminants.

Table 1 Colorimetric characteristics of the four illuminants used in Part 1

Nominal CCT (K)	CIE 1976 (*u*',*v*')	CCT (K)	D_{uv}	CRI R_a
2700	(0.267, 0.525)	2704	-0.0012	97
3500	(0.236, 0.516)	3516	+0.0030	97
5000	(0.208, 0.493)	4997	+0.0080	97
6500	(0.196, 0.471)	6514	+0.0054	98

Under each illuminant, an observer was first asked to look into the booth for two minutes, which could achieve 90% adaptation. Then the observer was asked to adjust the color of the center patch that was produced by the iPad using the four arrow keys on a keyboard until it appeared white. When the adjustment was complete, the experimenter instructed the observer to adjust one more step in each of the four directions to confirm the whitest appearance. The same procedure was repeated six times, with one for each display luminance level, in a random order. All the adjustments were started from an identical (*u*',*v*') setting, which appeared obviously chromatic regardless of the display luminance levels.

Eight observers (seven males and one female) between 22 and 28 years of age (mean = 24.3, std. dev. = 2.28) participated in this part of the study.

Part 2: High adapting luminance

An ARRI SkyPanel S60-C with an intensifier was placed above the viewing booth to produce five illuminants (i.e., CCT of 2700, 3500, 5000, 6500, and 8000 K) with a D_{uv} of 0.000 at 900 cd/m^2, which were calibrated using a JETI specbos 1511 UV spectroradiometer. Table 2 summarizes the colorimetric characteristics of the illuminants. The same procedure and display luminance levels in Part 1 were followed in this part. Six of the eight observers participated in this part of the study again.

Table 2 Colorimetric characteristics of the two illuminants used in Part 2

Nominal CCT (K)	CIE 1976 (*u*',*v*')	CCT (K)	D_{uv}	CRI R_a
2700	(0.269, 0.529)	2670	+0.0009	95
3500	(0.240, 0.511)	3485	-0.0008	90
5000	(0.215, 0.482)	5042	-0.0024	93
6500	(0.204, 0.466)	6501	-0.0015	94
8000	(0.197, 0.453)	8018	-0.0018	94

Results and discussions

Effect of adapting chromaticities, adapting luminance, and stimulus luminance

The chromaticities of the whitest stimulus at different luminance levels under different adapting conditions (i.e., adapting chromaticities and adapting luminance) were calculated in CIE 1976 (*u*',*v*') and in the *a*'-*b*' plane of CAM02-UCS (with an assumption of a complete chromatic adaptation, *D* factor = 1.0), as plotted in Figures 2 and 3.

When the adapting luminance was low, the chromaticities of the whitest stimulus all shifted away from the adapting chromaticities and tended to converge to a point beyond 7000 K. The lower the CCT of the adapting field, the larger the chromaticity shifts. When the adapting luminance was high, the chromaticity shifts from the adapting field to the whitest stimulus were much smaller.

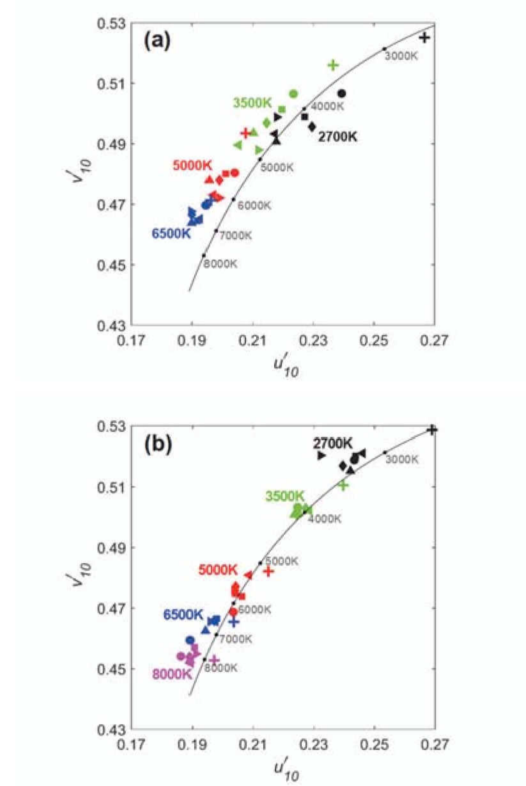

Figure 2 Average chromaticities of the stimuli that were adjusted by the participants at each display luminance level (● 100 cd/m^2 ■ 150 cd/m^2 ◆ 200 cd/m^2 ▲ 250 cd/m^2 ◀ 300 cd/m^2 ▶ 350 cd/m^2) under the low LA adapting conditions (+ adapting field) in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram. (A) Low L_A; (B) High L_A.

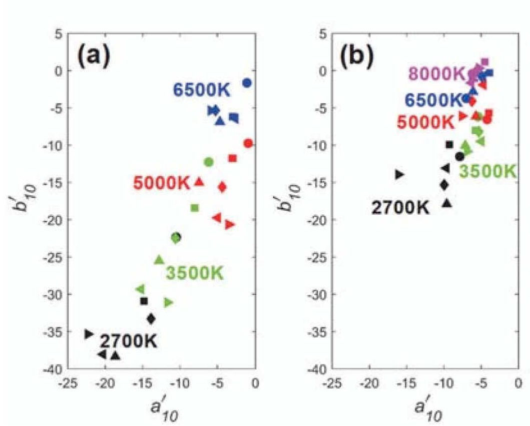

Figure 3 Average chromaticities of the stimuli that were adjusted by the participants at each display luminance level (● 100 cd/m^2 ■ 150 cd/m^2 ◆ 200 cd/m^2 ▲ 250 cd/m^2 ◀ 300 cd/m^2 ▶ 350 cd/m^2) under the low and high L_A adapting conditions with the chromatic background (+ adapting field) in the a'_{10}-b'_{10} plane of the CAM02-UCS. (A) Low L_A; (B) High L_A.

More importantly, the stimulus luminance also had an obvious effect, as shown in Figure 4. When the adapting luminance was low, a higher stimulus luminance introduced a larger chromaticity shift, especially under the adapting field with a lower CCT. The effect of stimulus luminance, however, was not obvious under the high adapting luminance level, as the chromaticities of all the whitest stimuli were close to each under each adapting condition.

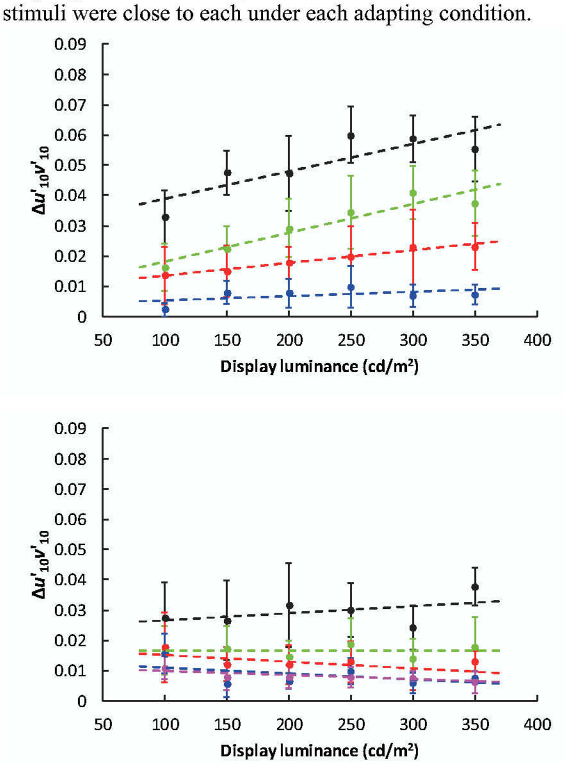

Figure 4 Chromaticity differences between the stimuli adjusted by the participants and the low L_A adapting conditions in the in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram versus the display luminance. Top: Low L_A; Bottom: High L_A.

Viewing mode, not viewing medium, affects white appearance

The speculation that different white points for display and surface colors were caused by the different degrees of chromatic adaptation due to different viewing media was obviously not supported by the findings in this study.

All the stimuli in this study were produced by an iPad display and all the observers were well aware that they were adjusting stimuli on an iPad display. If the viewing medium affected the white points, a lower degree of chromatic adaptation for viewing displays should always exist in this study and all the white points should converge to a chromaticity with a CCT of 6500 K or above, as found in many past studies, regardless of the adapting luminance and stimulus luminance. The chromaticities of the white points, however, varied with the stimulus luminance and the adapting luminance, as shown in Figures 2 and 3.

In addition, the chromaticities of the whitest stimuli at different luminance levels should be similar under a same adapting condition (i.e., adapting chromaticities and adapting luminance), as the degree of chromatic adaptation should only be affected by the adapting chromaticities and adapting luminance. It is obvious that the chromaticities of the whitest stimuli were greatly affected by the stimulus luminance, especially when the adapting luminance was low, as shown in Figures 2, 3, and 4.

Thus, the efforts to derive different degrees of chromatic adaption for different viewing media (i.e., displays versus surface colors) for explaining the differences in white points were not supported by this study, as different degrees of chromatic adaptation need to be modeled for different display luminance under a same adapting luminance.

If each stimulus luminance level was studied individually, the chromaticity shift direction and converge of the whitest stimuli under the low adapting luminance completely corroborated the past studies investigating the white appearance on displays. On the other hand, the chromaticities of the whitest stimuli were generally stable and much closer to the adapting chromaticities under the high adapting luminance, which completely corroborated the past studies investing the white appearance of surface colors. Thus, the different white appearance for surface colors and displays, as found in many past studies, were likely caused by the viewing mode.

Instead of focusing on the stimulus luminance, Figure 5 shows the chromaticity difference between the whitest stimulus and the adapting chromaticities under each adapting condition in the *a*'-*b*' plane of CAM02-UCS versus *J*'. It can be observed that the chromaticity shifts were generally smaller and stable for the stimuli having *J*' values below 100, since they were likely perceived as surface colors. For the stimuli having *J*' values beyond 100, the chromaticity shifts generally increased with *J*', since these stimuli were likely perceived as self-luminous stimuli. Such a trend was more obvious for the adapting conditions with a low CCT, which was consistent to the past studies on self-luminous displays. It is also interesting to see that the trend lines for the high adapting luminance conditions can well predict the chromaticity difference for the stimuli with a luminance of 100 cd/m^2 under the low adapting luminance.

The exact boundary or the transition zone for a stimulus to change from surface colors to self-luminous colors, as the zero gray point (G_0) mentioned by Evans, merits further investigations.

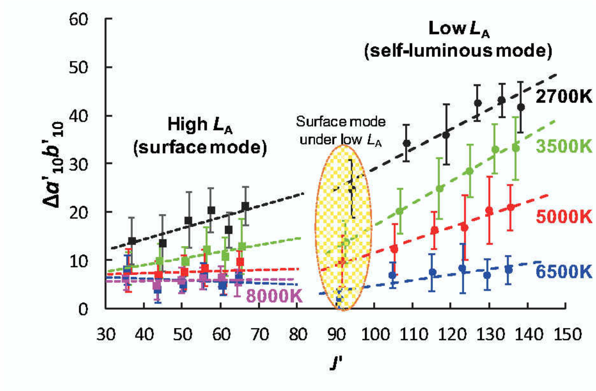

Figure 5 Chromaticity differences between the stimuli adjusted by the participants and the adapting conditions with the chromatic background in the a'10-b'10 plane of the CAM02-UCS versus the J' values of the stimuli.

A comprehensive color appearance model and uniform color space

The findings in this study suggested the necessity to develop a more comprehensive color appearance model to specifically address two issues.

- Degree of chromatic adaptation

The chromaticity differences under the two adapting luminance levels suggested a higher degree of chromatic adaptation under a higher CCT, which was consistent to the findings in several recent studies. A higher degree of chromatic adaptation under the high adapting luminance for the 2700 and 3500 K adapting conditions, as suggested by the smaller color differences, also corroborated the findings in many past studies and the computation of the degree of chromatic adaptation factor D in CIECAM02 and CAM02-UCS.

Furthermore, it seems that even the high adapting luminance still cannot introduce a complete chromatic adaptation under 2700 and 3500 K, as suggested by the fact that the chromaticity difference was not close to zero. Thus, it is worthwhile to further investigate how the adapting luminance and adapting chromaticities individually and jointly affect the degree of chromatic adaptation.

- Self-luminous stimulus

Though CAM02-UCS was used to characterize the chromaticity differences and the possible degree of chromatic adaption, such a uniform color space was developed for surface colors that had a luminance below the luminance of a perfect reflector under a same adapting condition and a lightness below 100. In other words, the larger chromaticity difference under the low adapting luminance conditions may be due to the invalidated uniform color space instead of a lower degree of chromatic adaptation under the low adapting luminance.

The boundary between surface colors and self-luminous stimuli needs to be studied. A comprehensive color appearance model and uniform color space needs to be developed for these self-luminous stimuli, which will play an important role in color reproduction for HDR imaging systems.

Conclusions

An experiment was carried out to investigate whether the different chromaticities for producing white appearance on displays and surface colors that were found in many past studies were really due to the different degrees of chromatic adaptation caused by the viewing media. Observers were asked to adjust the stimuli produced on an iPad display at different luminance levels under different adapting conditions (i.e., adapting luminance and adapting chromaticities) until they appeared white.

Though all the stimuli were produced by a self-luminous display, the chromaticities for producing white appearance varied with stimulus luminance and adapting luminance. When the stimulus luminance was relatively high in comparison to the adapting luminance, the chromaticities were similar to those in the past studies focusing on displays. When the stimulus luminance was relatively low in comparison to the adapting luminance, the chromaticities were similar to those in the past studies focusing on surface colors.

The results clearly revealed that the different chromaticities for producing white appearance were caused by the viewing mode of the stimulus, which was jointly affected by the stimulus luminance and adapting luminance, rather than viewing medium. Display stimuli were perceived as self-luminous stimuli when the stimulus luminance was relatively higher than the adapting luminance, while they were perceived as surface colors when the stimulus luminance was relatively lower than the adapting luminance.

The findings suggested the necessity to find the threshold that a stimulus would change from surface color to self-luminous color. Furthermore, a comprehensive color appearance model and uniform color space are needed for self-luminous stimuli, which are critically important to the color reproduction in HDR imaging systems.

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