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Real-world environment affects the color appearance of virtual stimuli produced by augmented reality

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Abstract

Color appearance models have been extensively studied for characterizing and predicting the perceived color appearance of physical color stimuli under different viewing conditions. These stimuli are either surface colors reflecting illumination or self-luminous emitting radiations. With the rapid development of augmented reality (AR) and mixed reality (MR), it is critically important to understand how the color appearance of the objects that are produced by AR and MR are perceived, especially when these objects are overlaid on the real world. In this study, nine lighting conditions, with different correlated color temperature (CCT) levels and light levels, were created in a real-world environment. Under each lighting condition, human observers adjusted the color appearance of a virtual stimulus, which was overlaid on a real-world luminous environment, until it appeared the whitest. It was found that the CCT and light level of the real-world environment significantly affected the color appearance of the white stimulus, especially when the light level was high. Moreover, a lower degree of chromatic adaptation was found for viewing the virtual stimulus that was overlaid on the real world.

Introduction

Great efforts have bene made to develop color appearance models for accurately characterizing and predicting the color appearance of stimuli perceived by the human beings. The investigation of color appearance models was originated from the observation that the color appearance of a stimulus varied under different viewing conditions [1]. Physical color stimuli, either produced using surface color samples or self-luminous displays, were used to derive various color appearance models and uniform color spaces, such as CIELAB, CIECAM02, and CAM02-UCS. In recent years, efforts have also been made to overcome some weaknesses in these models. For example, uniform color spaces have been developed to characterize the color differences of the stimuli in high dynamic range viewing conditions [2,3].

Due to the invention and development of reality technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), stimuli perceived by the human visual system do not have to be physical stimuli. With VR technology, a complete virtual environment can be created to replace the real-world environment and to fully immerse an observer. AR and MR, however, produce digital stimuli and overlay them on a real-world environment, so that both the digital stimuli and the physical stimuli are viewed simultaneously.

Given the wider adoption and usage of MR and VR, the color appearance of virtual stimuli is becoming more and more important. Though the physical stimuli in real-world environments whose color appearance is significantly affected by the color of the illumination or the adapting field, few study has investigated how the illumination in the real-world environments affects the color appearance of virtual stimuli produced by AR or MR technologies. This is critically important when a virtual stimulus is created to reproduce a physical stimulus and they are simultaneously viewed, few study has been conducted to investigate such an issue.

In this study, a psychophysical experiment was conducted to investigate the effect of the color and light level in a real-world environment affected the color appearance of a virtual stimulus that was overlaid on the real-world environment. Human observers were asked to adjust the color of the virtual stimulus until it appeared the whitest.

Method

Apparatus and setup

The experiment setup is shown in Figure 1. A viewing booth which and a spectrally tunable LED device were used to create different lighting conditions in a real-world environment. The viewing booth had dimensions of 60 cm (width) × 60 cm (depth) × 60 cm (height) and the interiors were painted with Munsell N7 spectrally neutral paint. The spectrally tunable LED device was placed above the viewing booth to produce a uniform illumination. A beam splitter and an iPad Air 2, which were mounted on a tripod, were placed outside the viewing booth. The iPad was horizontally placed and the beam splitter was rotated 45°, so that the beam splitter can produce a virtual image, which was produced by the iPad, on a vertical plane with a same size.

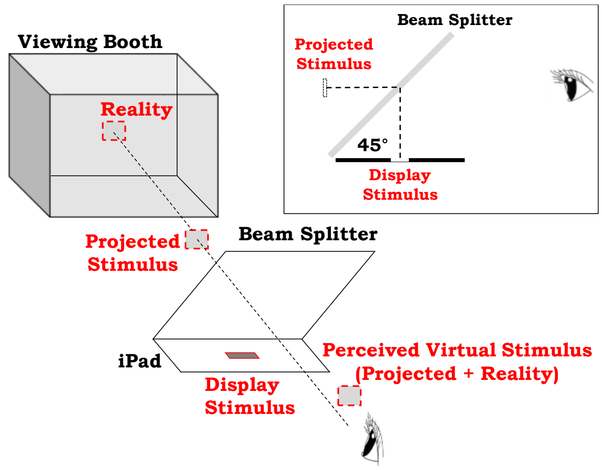


Figure 1 Schematic of the experiment setup. The virtual color was projected by the display colors through the beam splitter. The color perceived by the observers was a blending color of the virtual color and the booth color.

Figure 2 Photograph of the experiment setup. The stimulus was projected from the iPad through the beam splitter.

A Munsell N7 sheet, with a 3 cm × 3 cm opening being cut at the center, was placed on the iPad, so that the iPad produced stimulus through the opening. During the experiment, the observer was seated 40 cm from the tripod, with his or her chin being fixed on a chin-rest, so that the virtual image was perpendicularly viewed with a field of view (FOV) around 4°. Figure 2 shows the condition viewed by the observer.

The iPad was calibrated using a gamma-offset-gain (GOG) display model [4] and the CIE 1964 color matching functions (CMFs). With a customized program developed based on the GOG model, a Bluetooth keyboard was used to remotely adjust the chromaticities of the display along the u'_{10}-v'_{10} axes in the CIE 1976 u'_{10}-v'_{10} chromaticity diagram with a step of 0.001 unit. The luminance level of the display was fixed at 350 cd/m^2.

The beam splitter had a transmittance factor around 65% across the visible spectrum, as shown in Figure 3.

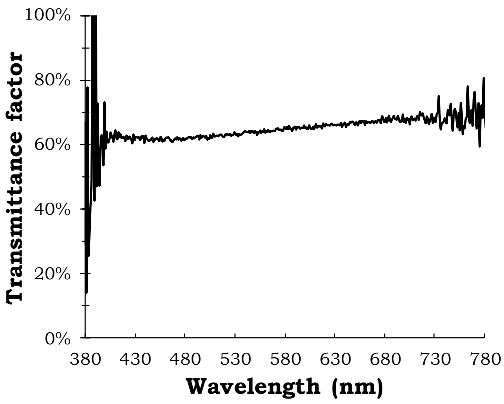


Figure 3 Spectral transmittance distribution of the beam splitter

Lighting conditions

Nine lighting conditions were created in this study, with one dark condition and the other eight being produced using the spectrally tunable LED device. These eight conditions comprised two levels of adapting luminance (i.e., L_w = 110 and 550 cd/m^2) and four CCT levels (i.e., 2700, 3500, 5000, and 6500 K), which were calibrated using a calibrated JETI Specbos 1411UV spectroradiometer and a calibrated Labsphere reflectance standard being placed at the place where the virtual stimulus appeared in the back wall of the viewing booth. The spectral power distribution (SPDs) SPDs of the eight lighting conditions were measured with and without the beam splitter from the observer's eye position. The measurements without the beam splitter were considered as the real-world environment (i.e., reality); the ones with the beam splitter were considered as the virtual environment viewed by the observers. The colorimetric characteristics are summarized in Table I, with the chromaticities being shown in Figure 4.

Though the lighting conditions were calibrated in the real-world environment, the adapting field is typically defined as the area surrounding the stimulus. Therefore, the virtual environments were considered as the adapting conditions.

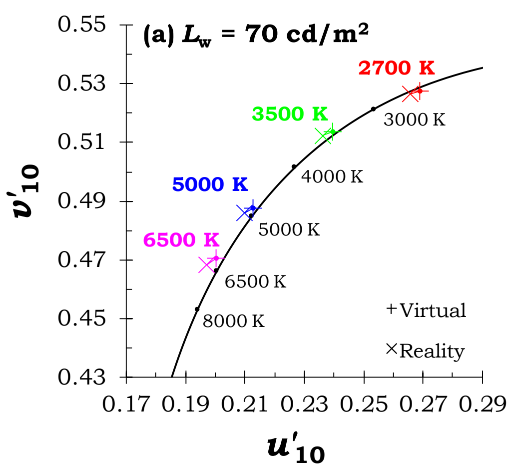
Table I Colorimetric characteristics of the real-world environments and the virtual environments viewed by the observers

(a) Reality (real-world environment in the booth)

Adapting condition	Luminance L_w (cd/m^2)	CCT (K)	D_{uv}
2700 K – low	107.8	2639	-0.002
3500 K – low	115.7	3476	0.000
5000 K – low	113.4	5043	+0.002
6500 K – low	108.2	6536	+0.004
2700 K – high	536.0	2606	-0.001
3500 K – high	547.5	3485	+0.002
5000 K – high	574.5	5029	+0.004
6500 K – high	559.0	6607	+0.005

(b) Virtual (virtual environment with the beam splitter)

Adapting condition	Luminance L_w (cd/m^2)	CCT (K)	D_{uv}
2700 K – low	68.8	2569	-0.002
3500 K – low	73.6	3362	0.000
5000 K – low	71.8	4847	0.000
6500 K – low	68.4	6221	+0.002
2700 K – high	342.0	2542	-0.001
3500 K – high	347.9	3369	+0.001
5000 K – high	363.6	4817	+0.003
6500 K – high	352.7	6284	+0.003



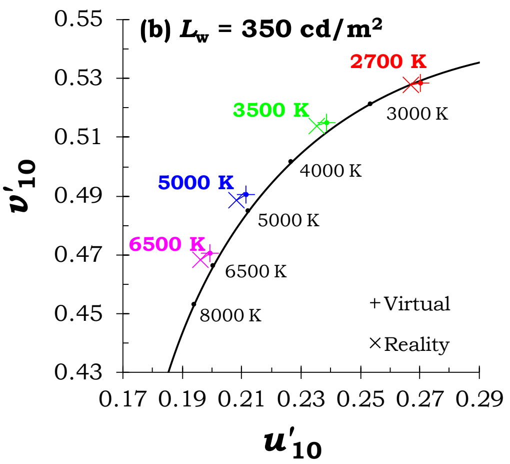


Figure 4 Chromaticities of the lighting conditions in the real-world environments and the virtual environments. (a) L_w = 70 cd/m²; (b) L_w = 350 cd/m².

Observers and experimental procedures

Nineteen observers (15 males and 4 female) between 20 and 29 (mean = 22.6, SD = 2.28) completed the experiment. Two observers had an abnormal color vision, as tested using the Ishihara Color Vision Test; their data were discarded in the analyses.

Upon arrival, the experimenter explained the procedure and tasks and guided the observer in front of the viewing booth. The observer completed the Color Vision Test and was then asked to fix his or her chin on the chin-rest. Under each lighting condition, the observer was instructed to look at viewing booth through the beam splitter for two minutes for chromatic adaptation, with the iPad being covered by a black sheet. After the adaptation period, the experimenter then removed the black sheet and randomly adjusted the chromaticities of the stimulus produced by the iPad. The observer was asked to adjust the color appearance of the virtual stimulus, which was the image produced by the beam splitter and the iPad, viewed in the viewing booth using the four keys on the Bluetooth keyboard until the color appearance of the stimulus appeared the whitest to him or her. Then, the experimenter helped the observer to confirm his decision by adjusting the chromaticity along the four directions for 1 unit (i.e., +0.001 u'_{10}, -0.001 u'_{10}, +0.001 v'_{10}, and -0.001 v'_{10}). For each observer, the experiment always started from the dark condition, which helped to reduce the time needed for dark adaptation. The sequences of the four CCT levels and the two light levels were randomized. In addition, the adjustments under the two 2700 K lighting conditions were repeated for evaluating the intra-observer variation.

Results

After the completion of the experiments, the SPD of each stimulus adjusted by the observers was measured under the corresponding lighting condition using the JETI specbos 1411UV spectroradiometer. The SPDs considered both the light produced by the LED device and the stimulus projected by the iPad display.

The intra-observer variation was characterized using the average color difference in the CIE 1976 u'_{10}-v'_{10} chromaticity diagram ($\Delta u'_{10}v'_{10}$) between the repeated adjustments made by each observer. It ranged between 0.0001 and 0.043 and had an average of 0.015. Figure 5 shows the one standard-error ellipses of the repeated adjustments under the two lighting conditions at 2700 K.

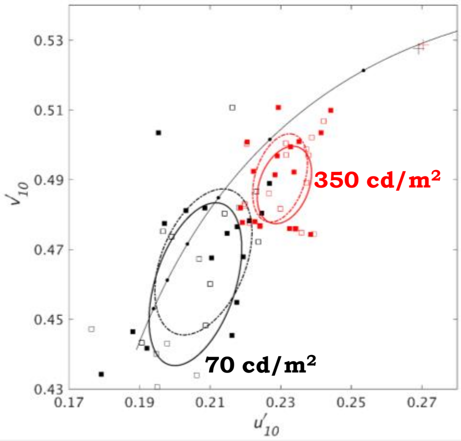
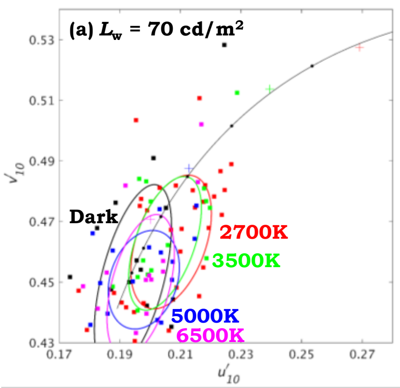


Figure 5 Chromaticities and the one standard-error ellipses of the repeated adjustments made by the observers under the two lighting conditions at 2700 K.

The inter-observer variation was characterized based on the adjustments made by each observer and the average adjustment made by the observers (i.e., an average observer) under each lighting condition using the mean color difference from the mean (MCDM) in the CIE 1976 u'_{10}-v'_{10} chromaticity diagram, as summarized in Table II. The adjustments made by the observers and the one standard-error ellipses under each lighting condition are shown in Figure 6. The MCDM values and the ellipse sizes were comparable to those in previous studies of white appearance and memory colors [5-8].

Table II Inter-observer variations in terms of the mean color difference from the mean (MCDM) in the CIE 1976 u'_{10}-v'_{10} chromaticity diagram under each adapting condition

Adapting condition		MCDM
Dark		0.0259
2700 K	Low L_w	0.0231
	High L_w	0.0130
3500 K	Low L_w	0.0210
	High L_w	0.0138
5000 K	Low L_w	0.0178
	High L_w	0.0091
6500 K	Low L_w	0.0206
	High L_w	0.0091



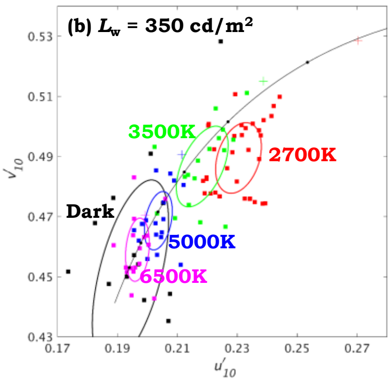


Figure 6 Chromaticities adjusted by the observers and the one standard-error ellipses under each lighting condition in the CIE 1976 u'₁₀-v'₁₀ chromaticity diagram.

The average chromaticities in the CIE 1976 u'_{10}-v'_{10} chromaticity diagram of the adjustments made by the observers under each lighting condition are as shown in Fig. 7. Note that the adapting chromaticities were those of the virtual environments. It can be observed that the chromaticities of the adjusted stimuli were generally below the blackbody locus, which was very different from many past studies investigating white appearance using surface colors and self-luminous colors. The stimulus adjusted under the dark condition was around to 8000 K. When adapting conditions had an L_w around 70 cd/m^2, the stimuli adjusted under the 5000 and 6500 K conditions were also around 8000 K, while those adjusted under the 2700 and 3500 K were close to 6500 K. When the adapting conditions had an L_w around 350 cd/m^2, the adjusted chromaticities shifted towards the direction of a lower CCT and were much closer to the adapting chromaticities.

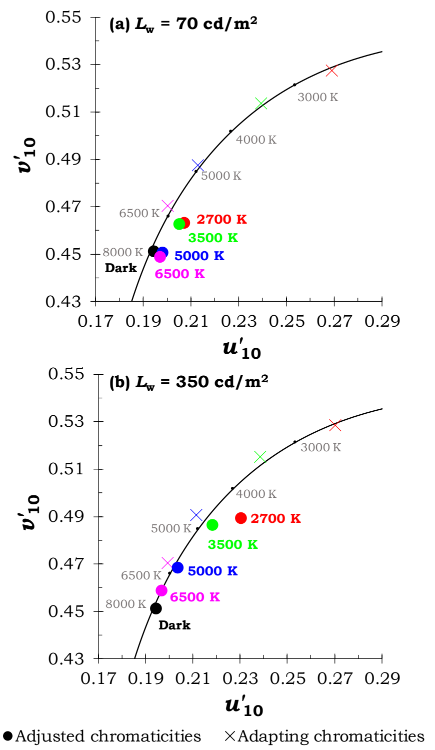


Figure 7 Average chromaticities of the adjusted stimuli under each adapting condition in the CIE 1976 u'₁₀-v'₁₀ chromaticity diagram. (a) L_w = 70 cd/m²; (b) L_w = 350 cd/m².

To consider the possible effect of the adapting chromaticities, the average chromaticities of the adjusted stimuli were also calculated in CAM02-UCS, with the degree of chromatic adaptation factor D being set to 1, as shown in Fig. 8. The CAT02 embedded in CAM02-UCS converted the stimulus luminance to lightness so that the effect of adapting luminance and chromaticities were considered. Under the adapting conditions with an L_w of 550 cd/m^2, the chromaticities were generally much closer to the origin of the a'_{10}-b'_{10} plane, which was the chromaticities of the adapting fields. The average chromaticity differences between the adjusted stimuli and the origin of the a'_{10}-b'_{10} plane, together with the 95% confidence intervals, are shown in Fig. 8.

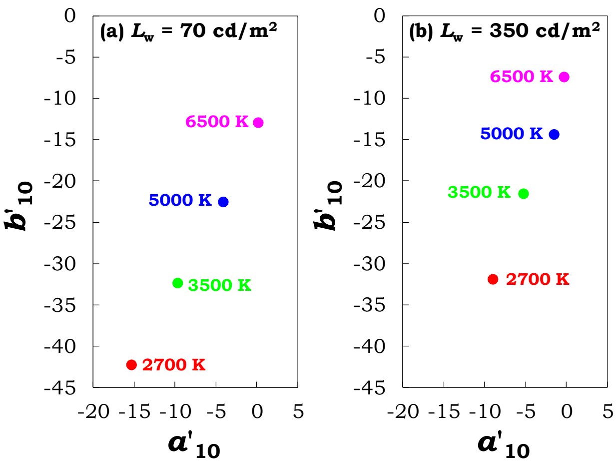


Figure 8 Average chromaticities of the adjusted stimulus in CAM02-UCS under each CCT level. (a) L_w = 70 cd/m²; (b) L_w = 350 cd/m².

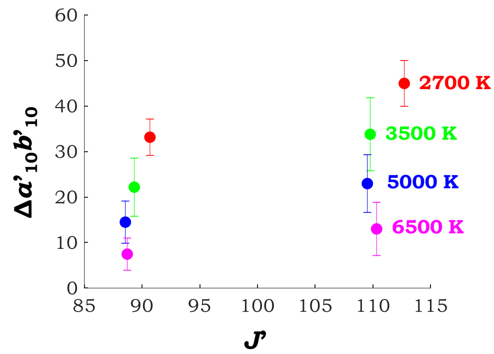


Figure 9 Chromaticity differences, together with the 95% confidence intervals, between the average chromaticities of the adjusted stimuli and the origin in the a'₁₀-b'₁₀ plane of CAM02-UCS.

Discussion

Adaptation to reality or virtual conditions

Since the virtual environments viewed through the beam splitter were around the virtual stimulus, the virtual environments were considered as the adapting fields in the above analyses. The observers, however, also viewed the lighting conditions in the real-world environments, which may also allow the observers to be adapted to the real-world conditions. Therefore, the chromaticities were also calculated using the virtual environments as the adapting conditions, as shown in Figures 10 and 11. It can be observed that when using the real-world conditions as the adapting fields, the lightness levels (i.e., J') of the stimuli were lower and the chromaticities were closer to the origin of the a'_{10}-b'_{10} plane.

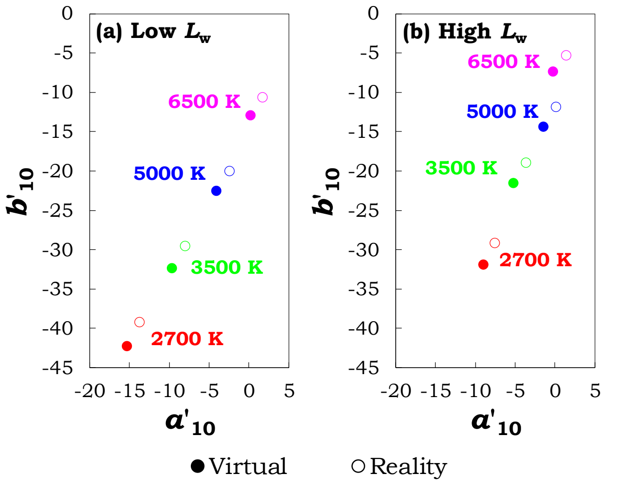


Figure 10 Average chromaticities of the adjusted stimulus in the a'_{10}-b'_{10} plane of CAM02-UCS. The solid markers represent chromaticities calculated using the virtual environments as the adapting conditions; the open makers represent those calculated using the real-world environments as the adapting conditions.

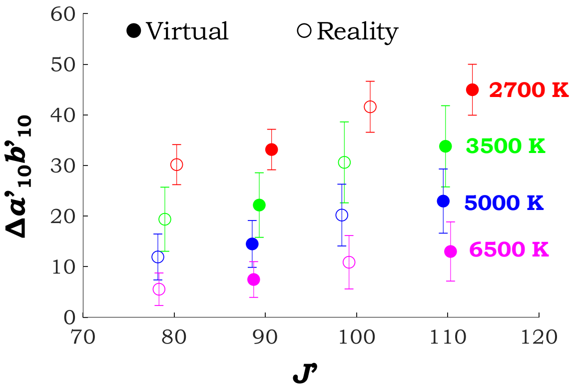


Figure 11 Chromaticity differences, together with the 95% confidence intervals, between the average chromaticities of the adjusted stimuli and the origin in the a'_{10}-b'_{10} plane of CAM02-UCS.The solid markers represent those calculated using the virtual environments as the adapting conditions; the open makers represent those calculated using the real-world environments as the adapting conditions.

Degree of chromatic adaptation for viewing physical and virtual stimuli

By comparing the adjusted chromaticities of the virtual stimuli in this study and those physical stimuli with similar lightness (J') levels in our previous study [9], the chromaticity differences between the stimuli and the origin of the a'_{10}-b'_{10} plane, as shown in Figure 11, revealed the effects of adapting CCT and light levels on the degree of chromatic adaptation when viewing physical and virtual stimuli.

When viewing virtual stimuli, the chromaticities adjusted under the adapting conditions with a higher CCT level and a higher light level were closer to the those of the adapting fields, which suggested a higher degree of chromatic adaptation. This finding collaborated the results in our previous study using physical stimuli [9]. The chromaticity differences between the adjusted white stimuli and the adapting fields, however, were always larger for the virtual stimuli when the adapting conditions were 2700 and 3500 K, in comparison to the physical stimuli, no matter whether the real-world environments or the virtual environments were regarded as the adapting fields. This may suggest that the color and light level of the adapting field may have a lower influence on the degree of chromatic adaptation and the color appearance of a virtual stimulus, since the stimuli may always appear self-luminous regardless of the adapting light levels.

Last but not the least, it would be worthwhile to investigate how the color appearance of a virtual stimulus would change under a fully immersive real-world environment.

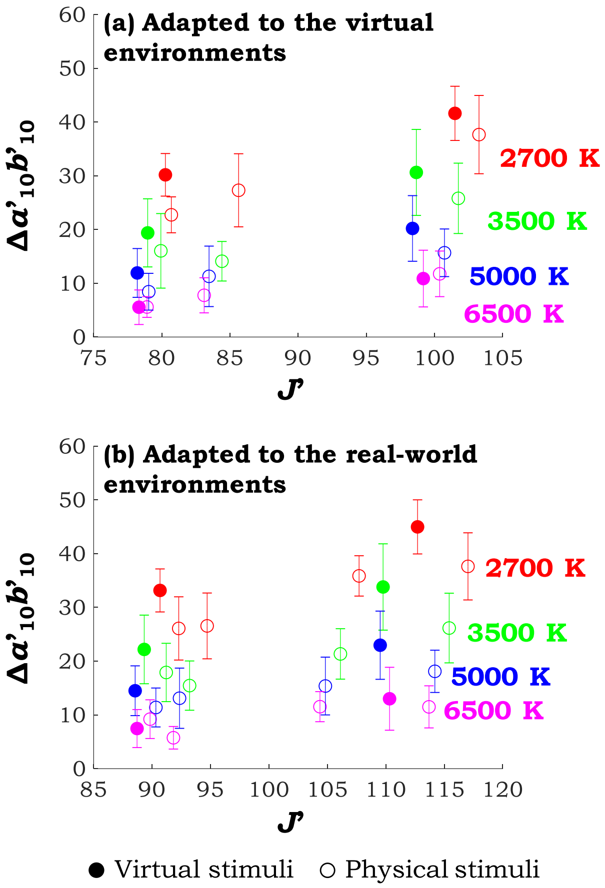


Figure 11 Chromaticity differences, together with the 95% confidence intervals, between the average chromaticities of the adjusted stimuli and the origin in the a'_{10}-b'_{10} plane. The solid markers represent the virtual stimuli in this study, and the open markers represent the physical stimuli in the previous study [9]. (a) The virtual environments viewed through the beam splitter were considered as the adapting fields; (b) The real-world environments were considered as the adapting fields.

Conclusion

This study aimed to investigate the color appearance of a virtual stimulus viewed under real-world environments with different CCT and light levels. An experimental setup was carefully designed to simulate a virtual stimulus produced by AR or MR technology. Human observers viewed the virtual stimulus under different real-world environments and adjusted the color appearance of the virtual stimulus until it appeared the whitest under each environment.

It was found that both CCT and light level of the real-world environment affected the color appearance of the virtual stimulus, which was similar to the studies investigating physical stimuli. When the light level was low, the chromaticities generally shifted towards the direction of a higher CCT along the blackbody locus and became further to those of the adapting fields, which was consistent to those in the previous study [9]. When viewing virtual stimuli, the degree of chromatic adaptation was found lower, in comparison to when viewing physical stimuli, which may due to the fact that the virtual stimuli cannot appear as surface colors under high adapting light levels.

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