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Comparison of remote and in-person tutorials of color appearance phenomena

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Abstract

Accurately describing the effect of lighting on color appearance phenomena is critical for color science education. While it is ideal to conduct in-person tutorials to demonstrate the color appearance fundamentals, laboratory tutorials have been limited due to COVID-19. The limitation of in-person gatherings and the increase popularity of remote teaching help evoke alternative methods to demonstrate color appearance phenomena. Here, a remote tutorial method is described, and results are compared to in-person tutorials. While the remote tutorial had weaker result in representing observers' color experience compared to the in-person lab tutorial, remote demonstrations can be used to demonstrate and discuss the limitations of color imaging, and the difference between the human visual system and digital imaging systems.

Motivation

The motivation of this project to test the feasibility of an alternative teaching method to demonstrate color science concepts. Color science is innately a visual topic. The goal of color science is to quantify human color perception through computational modeling and communicate precise color information to others. Despite the complex and computational nature of colorimetry, the core of color science is very straightforward: understanding, evaluating, and communicating the color of objects, light sources, and displays.

Color science education often includes the demonstration of color appearance phenomena (i.e., simultaneous contrast, Hunt effect, Bezold-Brucke hue shift, Abney effect, Helmholtz-Kohlrausch effect, Helson-Judd effect) and chromatic adaptation, which form the basis of color appearance models (CAMs) [1]. The demonstration of these (often subtle) effects require observers to be immersive in an environment where objects and light sources are manipulated. Instructors often control luminance of objects and background, and make decisions on the shape, size, surface optical properties, and texture of objects to achieve the intended effect. Therefore, the color demonstrations are often conducted in controlled conditions, such a research laboratory.

Unfortunately, the global outbreak of the respiratory disease named Coronavirus 2019 (COVID-19) disrupted in-person education worldwide. As a response to the global pandemic, e-learning and virtual demonstrations have gained substantial popularity in science education [2]. Color science education is a critical aspect of training new researchers and increasing interest to the field. This project aims to address the educational challenge of demonstrating color science concepts during the pandemic. A remote color tutorial is described and the results from a pilot study is compared to in-person tutorial.

Problem

The human visual system constantly adjusts itself to the external environment to make sense of the world. This constant calibration is known as visual adaptation, and it has several district modes related to lighting and color, such as light, dark, and chromatic adaptation. Chromatic adaptation is the change in the visual system's sensitivity to adapt to the changes in chromaticity of illumination. Chromatic adaptation helps maintain objects' color appearance approximately constant under different lighting conditions. Chromatic adaptation is arguably the most important color appearance phenomenon and can affect the perceived color of objects and light sources [1,3]. Research suggests that there are two stages of chromatic adaptation: a rapid mechanism that lasts less than a few seconds [4] and a second, slower mechanism that accounts for 50 % of total adaptation [5]. It is also suggested that this rapid adaptation can be asymmetric (i.e., adaptation to middle-wavelength is faster than adaptation to short and long-wavelength light sources) [6].

A general recommendation for color appearance experiments is to allow for full chromatic adaptation, which is 90% complete approximately between 60 s and 310 s [4,5,7]. Visible transitions between each trial can also introduce bias by cueing participants that the lighting conditions have changed. A dark period might be necessary between trials to reduce participant bias, although a very short period may not be enough to avoid retinal effects, such as afterimages [8].

A second color appearance phenomenon that is critical for imaging and non-imaging systems is the change in saturation with luminance, also known as the Hunt effect [9]. Objects seen under bright light appear more saturated, while under lower lighting conditions objects look desaturated. The Hunt effect is highly relevant for architectural spaces where low lighting conditions are preferred. For example, in museums, lower illuminance levels are required to reduce damage to artwork caused by optical radiation. However, decreased illumination levels cause artwork to appear duller and significantly different compared to daylight conditions.

In his original paper, Hunt predicted that, in practice, the saturation effect will be reduced due to a "compensating effect of the modification of the physical stimulus by the change of illuminant" [9], which implies the effects of the adaptation. He also noted that the spectral sensitivity of the photoreceptors was possibly not affected by adaptation, except for an overall factor independent of wavelength of the light source spectrum. The findings of his experiment suggested that a luminance-based constant can be used to adjust mathematical models that estimate the color appearance of surfaces. As a result, the colorimetric models can predict the Hunt effect, and indeed, constants have been incorporated into several existing colorimetric models, such as CAM02-UCS [10], iCAM06 [11], and CAM16-UCS [12].

Similarly, chromatic adaptation effects can also be simulated by applying chromatic adaptation transforms (CATs) to colorimetric models. The accuracy of CAMs in estimating chromatic adaptation and Hunt effect is often tested using psychophysical experiments [13,14], and further adjustments to the CAMs are made to improve estimation accuracy.

Chromatic adaptation and Hunt effect are critical aspects of color determination, specification, and metrication for both practice and research. Both of these color appearance phenomena are fundamental to the color science education, and lab demonstrations can provide much needed pedagogical support in science education, whether it is in-person or virtual [15-17]. Despite the importance of lab demonstrations, a recent limiting factor in science education was the prevention of in-person teaching due to COVID-19. While the global pandemic upset social, political, and economical spheres, education has risen above the challenges thanks to the imaging and telecommunication technologies. Remote learning tools have been increasingly used to deliver instructional lectures, but they can also be used to conduct lab tutorials with caveats. Here, the performance of a set of remote color appearance tutorials are compared to in-person tutorials.

Methods

Two color tutorials have been developed, conducted, and recorded in the Penn State Lighting Lab to demonstrate chromatic adaptation and the Hunt effect.

Lab Tutorials

Chromatic adaptation

Three adaptation lights and one test stimuli were generated by using an 11-channel multi-primary LED system (THOUSLITE® LEDCubes). The spectral power distribution (SPD) of the lighting conditions, shown in Fig. 1, were measured using a calibrated Konica Minolta® CL-500A illuminance spectrophotometer.

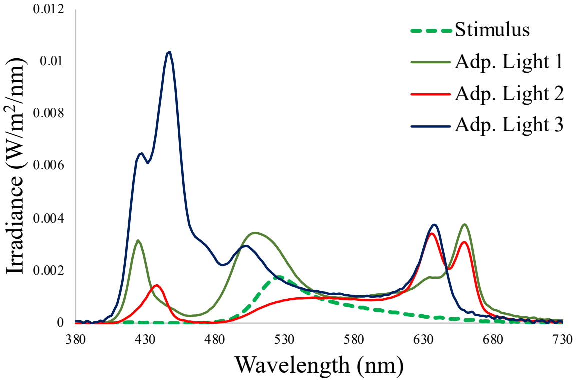

Figure 1. The spectral power distribution of the green test stimulus and three adapting lighting conditions.

The tutorials took place in an empty room in the Lighting Lab, where the lighting conditions were displayed to six participants (four males, two females) between the age of 18 and 30. Participants were students of a color science course, and they were not naïve to the purpose of the tutorial. None of the participants were compensated (neither cash nor course credit). Participants used the hue scaling method [18] to quantify the perceived changes in the appearance of a white disk on a neutrally painted wall (Munsell N8) illuminated by the green stimulus and three different adapting lighting conditions.

Prior to the tutorial, participants were trained to use the hue scaling method both on paper and under the light sources. Participants were positioned two meters away from the wall and judged the color of the white disk that has a 7 cm diameter, resulting in an approximate 2° visual field, as shown in Fig. 2.

The green colored stimulus was shown for 15 s followed by ten seconds of a dark period. After the dark period, one of the adapting lighting conditions was shown to participants for 2.5 minutes with ten seconds dark period in between each stimulus to prevent potential effects of afterimages. A text-to-speech script was used to provide automated voice commands to alert participants to make judgments.

Figure 2. Participants judging the green stimulus using the hue scaling method before and after adapting different lighting conditions.

Participants made a total of ten judgments: the green stimulus before adaptation, adapting light #1 after ten seconds, adapting light #1 after 120 seconds of adaptation, the green stimulus after adapting light #1, adapting light #2 after ten seconds, adapting light #2 after 120 seconds of adaptation, the green stimulus after adapting light #2, adapting light #3 after ten seconds, adapting light #3 after 120 seconds of adaptation, the green stimulus after adapting light #3.

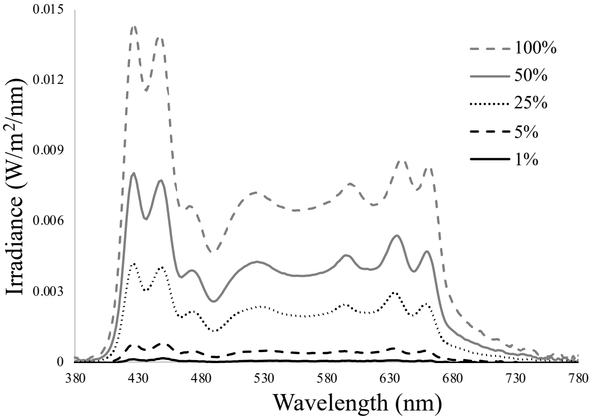

Figure 3. The spectral power distribution of the five lighting conditions with similar spectral power distribution shapes, but different illuminance levels.

Hunt effect

The same participants participated in the Hunt effect tutorial at the same time block. The order of the Hunt effect and chromatic adaptation tutorials were randomized (some participants attended Hunt effect tutorial first, the others attended chromatic adaptation tutorial first).

Table 1. Five lighting conditions were generated using dimming levels between 1 % and 100 % resulting in vertical illuminance levels between 6 lx and 499 lx.

Trial #	E_v (lx)	Dimming level (%)
1	6	1
2	33	5
3	157	25
4	289	50
5	499	100

Five stimuli were generated by using the same 11-channel LED lighting system. The spectral power distribution shape of each condition was held constant (Fig. 3) to prevent gamut-related saturation increase. The five lighting conditions varied in terms of vertical illuminance, ranging from 6 lx to 499 lx, as shown in Table 1. The vertical illuminance values were measured using a calibrated Konica Minolta® CL-500A Illuminance Spectrophotometer located on the wall (designated white disk).

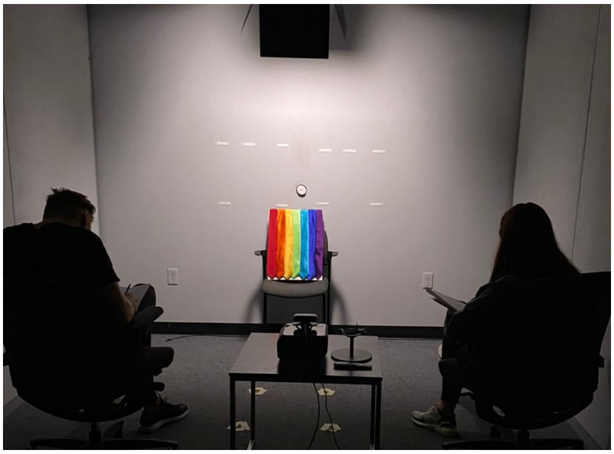

Figure 4. Participants judged the colorfulness of seven ties using the magnitude estimation method.

Participants used the magnitude estimation method [19] (ranging between 0 and 100) to judge the colorfulness of seven color samples circling the hue circle (red, orange, yellow, green, cyan, blue, purple) under five lighting conditions in a randomized order. The color samples were 50 cm x 38 cm in size, and it constituted an approximate 11° x 14° visual field, as shown in Fig. 4. The spectral reflectance functions of the seven color samples (shown in Fig. 5) were measured using a calibrated Konica Minolta® CM-26dG spectrophotometer. Each trial lasted 20 seconds, and there was a five-second dark period between trials.

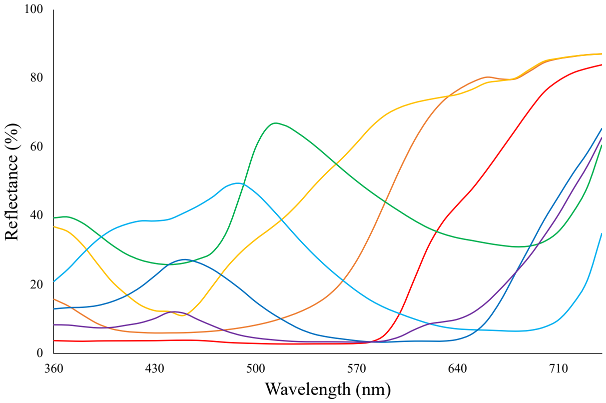

Figure 5. The spectral reflectance function of the seven color samples used in the Hunt effect tutorial.

Remote Tutorials

The Hunt effect and chromatic adaptation tutorials were run in the Lighting Lab when it was unoccupied and recorded using a Logitech® Brio 4K HDR webcam. The videos were recorded using Logitech® Capture software with HDR settings, anti-flicker at 60 Hz, no chroma key, or no auto white balance. The videos were in 1280 x 720 resolution, 60 fps, and MPEG AAC audio at 48000 Hz sampling rate and 16 Bits per sample to enable the automated voice notifications (to alert participants to make judgments). The files were saved in .MP4 formats and uploaded to Penn State's education website.

Eight participants (three males, five females) between the age of 18 and 30 took part in remote tutorials. Participants were students of a color science course, and they were not naïve to the purpose of the tutorial. None of the participants were compensated (neither cash nor course credit).

Instructions were provided to participants for both tutorials, where participants had to follow step by step instructions before running the tutorial at their homes. Participants were first asked to download the tutorial videos and marking sheets (for hue scaling and magnitude estimation methods) and print the sheets. They were directed to do the tutorials at night after eliminating all the light sources in a room. They adjusted the brightness of the display to maximum, deactivate automatic brightness and color adjustment, including software that controls color of display (e.g., *f.lux*), turn off software with notifications, prepare pen/pencil to mark judgments on the sheet, and run the tutorials which have audio instructions for judgments. The remote tutorials contain the same trials, timing, blackout between trials, and duration as the in-person tutorials.

Results

Chromatic Adaptation

The results from in-person and remote tutorials were plotted into a two-dimensional color gamut map – also known as a uniform apperance diagram [20]. Results show that three adapting lighting conditions appeared more neutral after two minutes of adaptation during in-person tutorials, as shown in Fig. 6. The reduction in the saturation of the perceived whiteness of light sources after two minutes indicates that even highly chromatic light sources can be affected by adaptation, depending on the context and adaptation state of the observers.

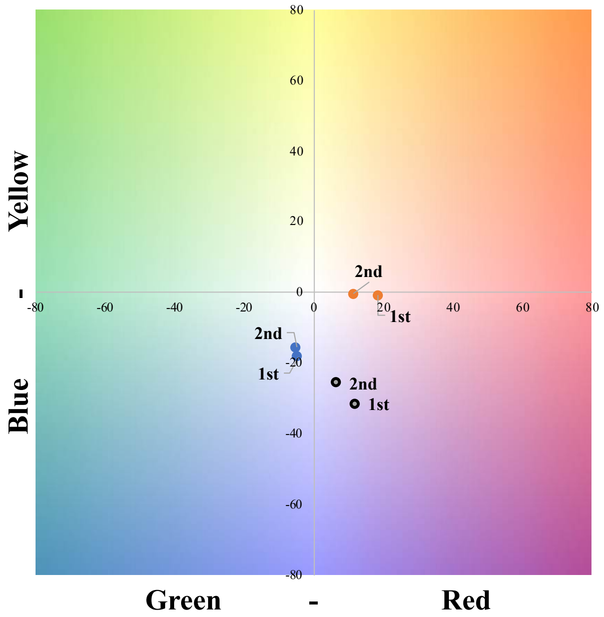

Figure 6. Results of in-person chromatic adaptation conducted in the Lighting Lab for white surface. Blue dots are adapting point #1, orange dots are adapting point #2, and black dots are adapting point #3. The first measurement was done after ten seconds of chromatic adaptation, and the second measurement was done after 2.5 minutes of chromatic adaptation.

The perceived color of the adapting lighting condition in remote tutorials were more saturated compared to in-person tutorials, as shown in Fig. 7. The direction of the perceived saturation of the stimuli was mostly towards to the white point (except adapting light #1), but the adaptation effects were smaller in magnitude. The results indicate that remote tutorials for chromatic adaptation is limited in replicating immersive human color experience. Despite the smaller magnitude of adaptation, some of the participants noted that the tutorial was intense but illustrative, due to the highly chromatic nature of the stimuli.

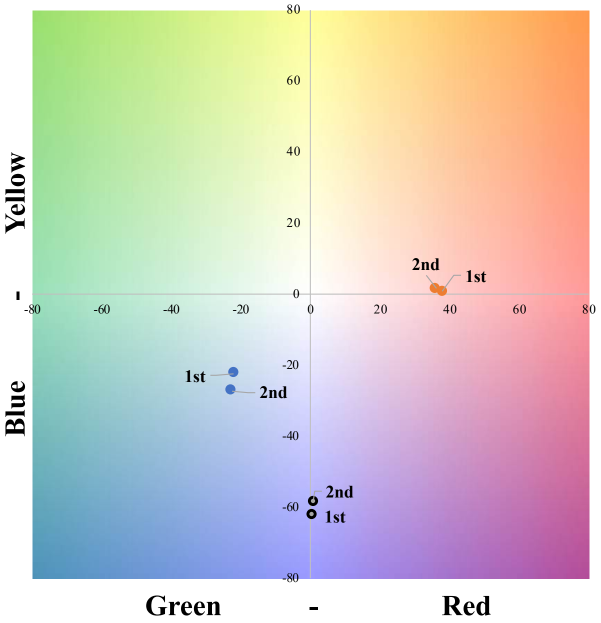

Figure 7. Results of the remote chromatic adaptation tutorial for white surface. Blue dots are adapting point #1, orange dots are adapting point #2, and black dots are adapting point #3. The first measurement was done after ten seconds of chromatic adaptation, and the second measurement was done after 2.5 minutes of chromatic adaptation.

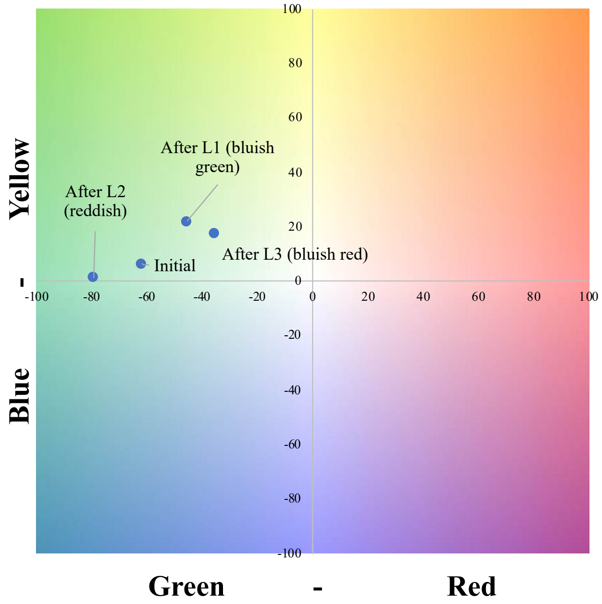

Figure 8. The perceived color of the green stimulus (initial) changes in different direction depending on the color of the light source in the lab tutorial. After adapting to lighting condition #1 (L1) which was reddish white, the stimulus is perceived to be greener that the initial condition. After adapting to lighting condition #2 (L2) which was bluish white, the stimulus is perceived to be yellower that the initial condition. After adapting to lighting condition #3 (L3) which was bluish-reddish white, the stimulus is perceived to be less green that the initial condition.

Similarly, the perceived appearance of the green stimulus was characterized after ten seconds and 2.5 minutes of adaptation to each lighting condition. Participants who attend the in-person tutorial perceived the green stimulus to be greener after being exposed to a reddish adapting light (L2), as shown in Figure 8. After adapting to a bluish-green adapting lighting condition (L1), participants found the green stimulus to be yellower. After adapting to a bluish-red adapting lighting condition (L3), participants found the green stimulus to be less green (more neutral). All the changes to the perceived stimulus follow the opponency process of the human visual system and can be explained by the adjustments at retinal and neural levels [21]. In the remote tutorials, the opponency effects were in the similar direction, but they were less pronounced, as shown in Fig. 9.

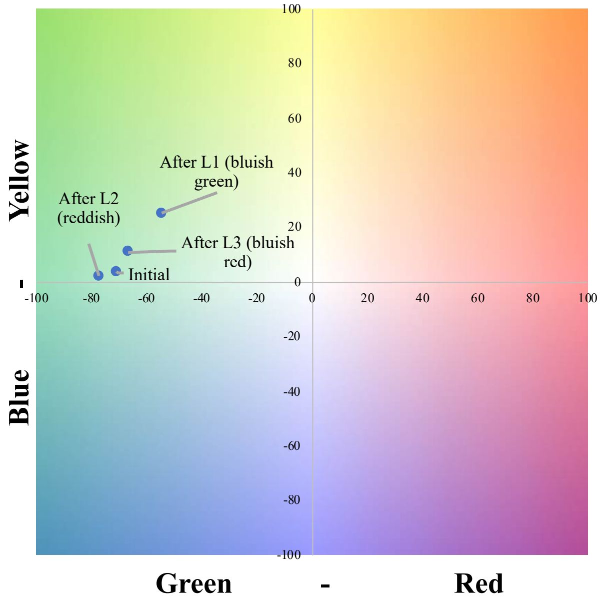

Figure 9. The perceived color of the green stimulus (initial) changes in different direction depending on the color of the light source in the remote tutorials. The perceived difference in the green stimulus is smaller compared to the in-person tutorials, shown in Fig. 7. Lighting condition #1 (L1) was reddish white, lighting condition #2 (L2) was bluish white, and lighting condition #3 (L3) was bluish-reddish white.

Hunt Effect

The Hunt effect tutorial results were plotted as a function of light intensity to compare the perceived colorfulness of objects under varying levels in remote and in-person tutorials. For the participants who attended the tutorial in the lab, the colorfulness of the objects and light intensity had a power relationship, as shown in Fig. 10. The fitted regression line had a coefficient of determination $R^2 = 0.941$. The error bars show the standard error of the mean.

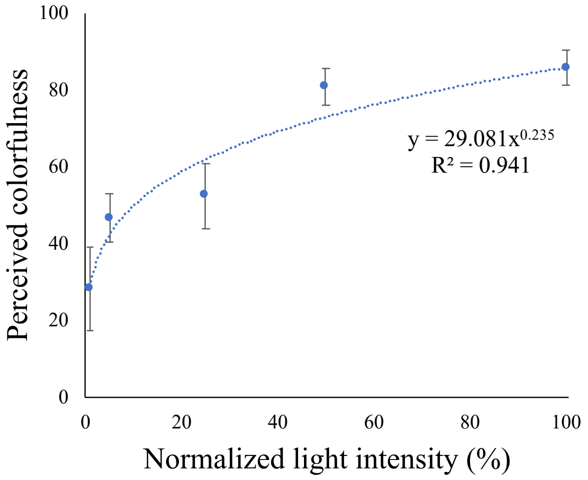

Figure 10. The relationship between the normalized light intensity and perceived colorfulness of objects for in-person tutorial has a fitted regression line of $R^2 = 0.941$. The error bars indicate the standard error of the mean.

For the remote tutorials, the colorfulness of the objects and light intensity had a similar power relationship, as shown in Fig. 11. Although the coefficient of determination of the fitted regression line was $R^2 = 0.734$, and the participants noted that differences between trials #3, #4, and #5 (25%, 50%, and 100% light intensity, respectively) were not perceptible. The overlapping error bars in Fig. 10 (the standard error of the mean) indicate that the differences between trials #3, #4, and #5 may not be significant.

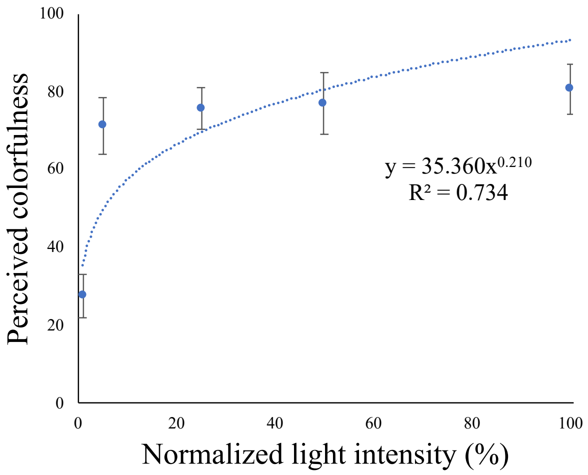

Figure 11. The relationship between the normalized light intensity and perceived colorfulness of objects for remote tutorial has a fitted regression line of $R^2 = 0.734$. The error bars indicate the standard error of the mean.

The perceived colorfulness of the objects in both tutorials seem to follow a logarithmic function rather than a linear relationship. The findings support the previously established visual relationships, such as Steven's power law [22] or Weber-Fechner's logirhmic law [23]. It should be noted that the power or logarithmic relationships between physical stimulus and magnitude of perception can be affected by context, surround, and complexity of the stimuli [24].

Conclusions

Demonstrating color appearance phenomena, such as chromatic adaptation and Hunt effect, are critical parts of color science education. The limitations of in-person lab tutorials and the increase in online education might provide an alternative method for conducting lab tutorials remotely.

Results from in-person and remote color appearance tutorials indicate that adaptation affects the perception of chromaticity for both tinted white and chromatic stimuli. Remote chromatic adaptation tutorials were limited in demonstrating the immersive color experience, but the oversaturated recordings made an impression and created a positive educational opportunity for students.

Hunt effect exhibited a power function in both remote and in-person tutorials. Results were weaker when participants attended tutorials at home remotely, due to the limitations of recording and lack of control over display color management on participant's end.

Limitations of the study include a small sample size and lack of desaturated color samples for Hunt effect tutorial. Despite the limitation of the tutorials, results are encouraging in that a relatively low-budget tutorial can be designed and conducted in the comfort of observers' home.

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Dorukalp Durmus received his PhD in architectural sciences from the University of Sydney (2018). He worked as a postdoctoral associate in the Pacific Northwest National Laboratory (PNNL) before joining the Department of Architectural Engineering at Penn State University as an assistant professor. His work focuses on colorimetry, visual perception, adaptive lighting systems, and human factors in illumination engineering. He is a Fellow of the Higher Education Academy (FHEA) and awarded HJ Cowan Architectural Science scholarship.