JOSA COMMUNICATIONS

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Museum lighting: Why are some illuminants preferred?

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We had shown earlier that viewers prefer to look at artworks under illuminants of ~3600 K. In the latest paper we tested the hypothesis that the preferred illuminant is one that appears neither warm nor cool and repeated the settings at each of four illuminances to test the stability of the findings. Observers looked at a neutral white reflectance standard hung on a matte-gray wall lit by overhead banks of lamps whose combined value could be adjusted continuously between 3000 and 4400 K while illuminance was kept constant. Illuminance ranged from 50 to 2000 lux. Observers adjusted color temperature until they were satisfied that the standard looked neither warm nor cool. The mean for a group of eight observers was approximately 3700, independent of intensity; this corresponds to a dominant wavelength of ~580 nm. In a separate study four observers scaled the apparent warmth or coolness of flashes of equiluminant monochromatic lights; the warm–cool transition was between 560 and 580 nm; warmness was completely predicted by the perceived redness of each light as derived from hue and saturation scaling functions from the same group.

OCIS codes: 330.0330, 330.1710, 330.5020.

1. INTRODUCTION

Curators and exhibit designers must take into account many factors in how artworks are displayed. One aspect is how the displays are lit, and this is the focus of our research. There are two constraints on the way in which artifacts displayed in museums are lit: conservation and aesthetics.[1] Typically the lighting has a color temperature of ~3000 K and illuminances between 100 and 300 lux. Current practice is often based on a canonical set of illumination functions by Kruithof that are said to yield the most pleasing illumination.[2] These functions show that the preferred range of color temperatures varies with illuminance. At 50 lux the range is 2200–2500 K, whereas at 2000 lux it is from 3500 to more than 10,000 K; the midpoint of the range at 200 lux is the widely used 3000 K. But Kruithof did not deal directly with museums or aesthetics; he simply claimed to specify optimal illumination in the workplace, assuming that something neither warm nor cool was best. More recent attempts to verify Kruithof's findings have also concentrated on room illumination; findings were often contradictory, and when intensity was varied, the values were outside the range acceptable for museum lighting.[3] Some of the contradictions may also stem from the fact that color temperatures were not continuously adjusted.

Although most papers on museum lighting acknowledge the importance of satisfying the viewing public, the emphasis is on conservation. Few explore the public's perceptions of the lighting, and still fewer directly manipulate the lighting to find the optimum. For example, one attempt at measuring viewers' satisfaction was simply based on surveys of visitors' opinions in different museums, relying on lighting variations among the institutions.[4] Intensities are typically low in order to prevent damage, but within this constraint it is possible to vary the spectral distribution of the lighting. In our earlier work we systematically manipulated color temperature of the illumination and measured the effects on the preferences of viewers of artworks.[5] We simulated a museum environment in miniature, and observers either compared the appearance of the same painting under different illuminants in adjacent rooms or rated the appearance of paintings seen one at a time under different illuminants. Illuminance on a picture was approximately

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200–250 lux at one of 11 color temperatures ranging from 2500 to 7000 K, representing "white" lights from early morning sunlight to light from a blue, cloudless northern sky. Results were quite clear: Observers preferred a color temperature of ~3600 K. The result held true across a large variety of paintings. It was also unaffected by preadapting the visual system to different illuminants (2800, 3600, and 5800 K) to mimic the effects of moving from one room to another with different illuminations.

All our findings described above were based on one illuminance, ~200 lux to approximate the museum norm. Also, color temperature was varied in rather coarse steps of roughly 400 K. Pilot observations with lights whose color temperature could be continuously varied from 3000 to 4400 K indicated a preferred color temperature whose value was slightly higher than 3600 K. This still leaves two central questions: Why is the preferred illuminant of the order of 3700 K, which does not correspond to any widely encountered artificial or natural illumination? Further, does the preferred illuminant vary with intensity within the range of museum lighting?

On the basis of Kruithof's[2] criterion as well as some of our informal observations, the current study tests the hypothesis that an illuminant of ~3700 K is one that is perceived as neither warm nor cool. We also test whether this value varies with intensity over a range that includes typical museum levels.

Finally, since 3700 K is far from achromatic, we examine how the dimension of warm–cool relates to color appearance. For other reasons we had also been interested in how various perceptual processes might relate to color appearance. For example, color is often used to code noncolor dimensions, such as temperature or elevation. We have been examining whether there are intrinsic connections between these seemingly disparate dimensions. Here we examine specifically the connection between perceived warmth and hue and saturation, which are dimensions of color vision that can be related directly to spectrally opponent mechanisms in the visual system.[6] As part of those studies we had asked whether there was a reliable correlation between perceived warmth or coolness and the hue and saturation of spectral lights. We include those data as a validation of our findings about perceived temperature of "white" lights.

2. METHODS

A. Illuminant Adjustment

1. *Apparatus*

An observer sat in a small room facing a "wall" (square board 1.25 m across) painted neutral matte-gray (~20% reflectance). The observer's eyes were approximately level with a neutral white reflectance standard (Photo Research; diffuse reflectance close to 100%) at the center of the gray wall. At the viewing distance of 80 cm the circular white standard covered 3.5° of the observer's visual field; the wall subtended approximately 75°.

The only illumination in the room was from two banks of tungsten–halogen lamps. One bank contained 50 W, 12 V, MR-16 lamps (Solux) nominally rated at 4700 K; the other bank's lamps, 35 W, were nominally 3000 K. The observer used a small control keypad to change the ratio of voltages provided to the two banks such that illuminance remained approximately constant while color temperature changed continuously from one limit to the other. The keypad had two buttons, one of which increased color temperature and the other decreased it; there were approximately 100 steps between the two extremes. Following the observer's adjustment we recorded the voltages to the two banks of lamps and used those values to derive the chosen color temperature by interpolation on our smooth voltage/color temperature function. This function was obtained from calibrations performed with a computerized scanning spectroradiometer (Photo Research, model PR-703A/PC) aimed from the observer's position at the white reflectance standard. Illuminances and color temperatures were measured at each of 22 driving voltages across the range from zero to full output from any one bank of lights; these data were then smoothed with a fourth-order polynomial.

We show in Fig. 1, the spectral distributions of the lights set at one extreme or the other, as well as the distribution for the illuminant chosen by our observers as best meeting the experimental criterion (see below). The curves are smooth, as is the transition from one extreme to the other; no illuminant differed by more than 0.005 uv units from the locus of blackbody radiators.

Illuminance varied slightly over the full range of color temperatures: Mean illuminance was roughly 2000 lux, with the highest value (at 3000 K) exceeding the lowest (at roughly 4200 K) by a factor of 1.5. However, across the crucial range (see Section 3) from 3200 to 4200 K, illuminances differed only by a factor of 1.08. To obtain illuminances effectively lower than 2000 lux, observers viewed the white standard through neutral density filters (Inconel) that reduced light reaching the eye by the requisite amount; since these filters are spectrally neutral, they did not affect color temperature. Filters were mounted on large goggles worn by the observers. For 2000 lux, the filter was thin, clear glass; the neutral density filters further reduced intensities to give effective illuminances of 500, 200, and 50 lux.

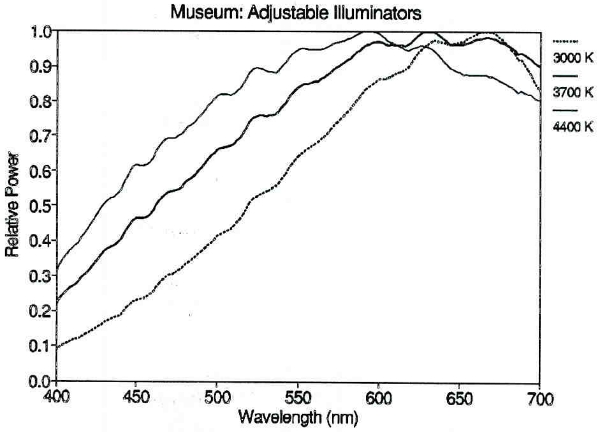


Fig. 1. Spectral distributions of the illuminators set at each of the end points of the available color temperature range and at the color temperature of the observers' mean experimental settings.

2. *Procedure*

In any given session only one of the four illuminance levels was used, and the observer was fully adapted to that level (viewed the scene for at least 5 min) before making any adjustments. The sequence of illuminances was randomized for each observer.

In each session observers adjusted the color temperature of the illuminant in four blocks of trials. Each block consisted of three adjustments, each beginning at one of three starting points (3000, 3600, or 4400 K; random order). Observers were instructed to look at the white standard and adjust the lighting until the white standard appeared neither warm nor cool. They could adjust the illuminant's color temperature up and down as far and as often as they liked until they found a satisfactory point. The first block constituted a practice block, and its data were not included in analyses; thus observers' choices for each illuminance were means of nine settings. At the start of each adjustment trial the observer was given a remote keypad that controlled the voltages.

3. *Observers*

Eight observers participated in this study; ages ranged from 16 to 32 yr; five were female; all had normal vision as evaluated by a full battery of vision tests: optometric evaluation, contrast sensitivity across the spatiotemporal domain, hyperacuities (including vernier acuity, stereoacuity for crossed and uncrossed disparities, minimum motion detection), and color vision (including D15, desaturated D15, and 100-hue panel tests, anomaloscope, and color appearance scaling). Two had participated in our earlier study in which they rated the appearance of paintings under fixed illuminants.[5] Although all but one of the observers were college educated and had participated in other psychophysical studies, none had special expertise in art or lighting; they represented a cross section of the general museum-going public.

B. Perceived Temperature and Color Appearance

1. *Apparatus*

Observers viewed stimuli presented in a Maxwellian-view optical system. The source was a tungsten–halogen lamp whose light passed through a grating monochromator (Jarrel-Ash, Ebert type, 1/4 meter). Luminance was controlled by varying the voltage to the lamp; some of the output from the monochromator was diverted to a photocell whose output was used by the experimenter to adjust luminance at the start of each trial. Blocking filters were used at the spectral extremes to maintain purity of the stimuli. Digital timers and an electromagnetic shutter controlled duration. High-contrast photographic plates in the beam's field plane determined stimulus size. An additional beam provided a continuously visible fixation target: four small, dim, achromatic lights arranged in a "cross" at the center of which the stimuli appeared.

2. *Procedure*

Temperature scaling. In two sessions, each observer rated the degree to which each monochromatic light appeared either warm or cool. Following 10 min of dark adaptation at the start of the session, observers scaled the appearance of monochromatic lights subtending 1° and presented as 500-ms flashes against a dark background, with an inter-flash interval of 15 s preceded by a warning tone. All were equated for a retinal illuminance of 25 Td. Wavelength varied from 440 to 660 nm in 10-nm steps. In each session these stimuli were presented in five blocks with order randomized within a block. The first block was practice to familiarize the observer with the procedure and the range of stimuli; only data from the remaining four blocks were analyzed.

After each flash the observer stated whether the light appeared warm or cool and then rated the strength of that sensation on a percentage scale. Since the entire procedure was repeated, the total number of ratings of each stimulus was eight.

Hue and saturation scaling. Each observer characterized the color appearance of spectral lights, using our procedure of direct hue and saturation scaling.[7,8] The procedure was the same as for temperature scaling, except that after each flash the observer scaled its appearance by reporting the percentages in his or her sensation of red, yellow, green, or blue for a total of 100%; he or she then stated, separately, apparent saturation, that is, total chromatic content as a percentage of the sensation elicited by the stimulus just seen. No specific training was given other than simple practice without feedback, nor were any of the terms defined beyond their common everyday meanings. We have shown that this procedure, even with naïve observers, yields highly reliable ratio scales from which canonical measures of color discrimination can be derived.[8,9] Since this was all done in one session, each observer's hue and saturation values were means of four repetitions. A standard arc-sine transform, used to normalize variances associated with bounded scales, was applied to each value before averaging.[8,10] For convenience we sometimes reapportion the hue data so that they include saturation: Each hue percentage is multiplied by its associated percent saturation; thus, for each stimulus, the sum of the hues equals saturation. This transformation is acceptable because we have shown that with our procedures, observers produce ratio scales of sensation.[8]

3. *Observers*

There were four observers, two females and two males, and age range was 17–27 yr. All had normal color vision. All had participated in studies that used a variety of scaling procedures.

3. RESULTS

The central purpose of this study was to find the color temperatures of illuminants that appeared neither warm nor cool. The major findings are shown in Fig. 2, which shows the group's average settings of the illuminant as a function of the illuminance on a white standard. Observers' chosen color temperatures were first averaged across the values obtained for each of the three starting points, and these individual averages were used to derive the group means.

The dotted lines above and below the mean function represent group standard deviation boundaries. Owing

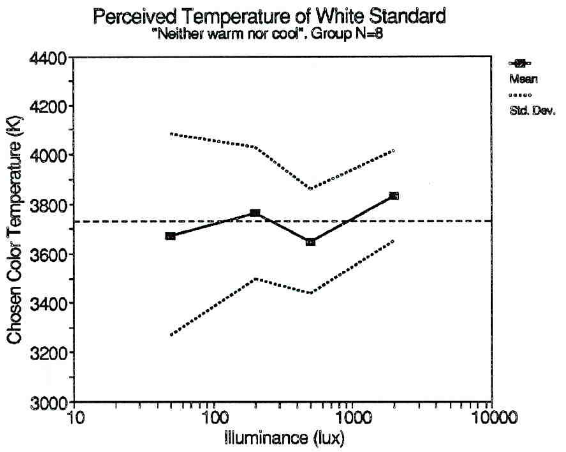


Fig. 2. Color temperature of illuminant chosen to appear "neither warm nor cool." Observers viewed a neutral white standard while adjusting the illuminant at each of four illuminances. Mean settings are given for a group of eight observers. Dotted lines are boundaries for ±1 group standard deviation. The horizontal dashed line is the overall mean choice.

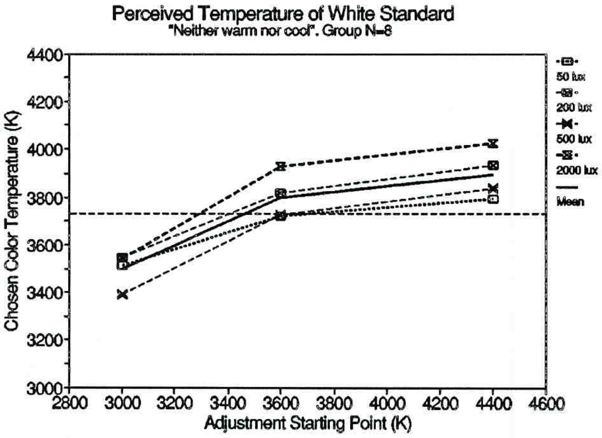


Fig. 3. Data in Fig. 1 broken down to show effects of starting point on final choice. Trials that started with lights set at 3000, 3600, and 4400 K were averaged separately. Data were analyzed separately for each level of illuminance on the white standard viewed by the observers. The solid line shows the overall mean.

to the small size of the group ($N = 8$), these boundaries overstate the degree of variability: Only one observer had a mean setting below 3100 K at one of the illuminances, and another had a single value above 4200 K.

Clearly, the choice of an illuminant that appears neither warm nor cool is stable across observers and across illuminances. The central tendency of these choices is given by the dashed horizontal line, which is the mean collapsed across illuminance and has a value of 3730 K.

Figure 3 breaks down the data by starting point for each setting. As with many psychophysical adjustment procedures, there is an anchor effect. For example, for trials that began at 3000 K, the values finally chosen were approximately 3500 K, whereas for the starting point at 4400 K the choice was approximately 3900 K. But this was always in the direction of 3700 K, which is seen most clearly for those trials that began at 3600 K. Again, there is no major effect of illuminance. While 3700 K is roughly in the middle of the available color temperatures, the overall result is not simply a range effect: Observers usually adjusted past the warm–cool transition and then returned to it, often doing so several times; also, 3700 K is not in the middle of the range of voltage adjustment steps—different numbers of button pushes are needed to reach it from different starting points.

For the above data, observers were adjusting the overall illumination in the room. Under those conditions, the white standard appeared roughly but not completely achromatic. We measured the spectrum when the lights were set at the mean value of slightly more than 3700 K: That illuminant, with respect to an equal-energy white, had a dominant wavelength of ~580 nm at a purity of 35%. When such a light is viewed as a small, isolated stimulus it does not appear achromatic. It appears quite yellow.

We studied the apparent temperature of chromatic stimuli by asking observers to rate the degree to which monochromatic lights appear neither warm nor cool. The mean data from a group of observers are shown in Fig. 4 together with standard error of the mean boundaries. The agreement among observers is very high and shows that somewhere between 550 and 580 nm the appearance of spectral lights shifts from warm to cool.

To interpret the findings in Fig. 4, we examined the hue and saturation functions from the same group of observers when they scaled the color appearance of the same monochromatic lights. The results are shown in Fig. 5(a). For this figure, each observer's hue functions were reapportioned by that observer's saturation function so that at each wavelength the sum of the hue values equals the saturation (see Section 2). In Fig. 5(b) we replot the mean cool and warm functions together with the curve for red in Fig. 5(a). We show both the value for red alone presented in its original form unscaled by saturation and, as shown in Fig. 5(a), where it has been modified by the saturation values. A spectral light appears warm only when it elicits some sensation of redness. This is further evident at short wavelengths, where coolness begins to di-

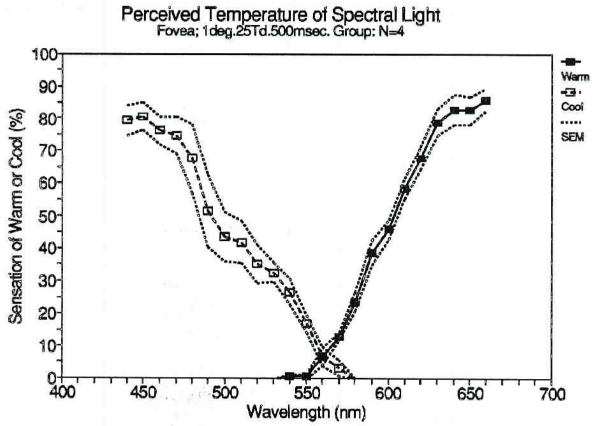
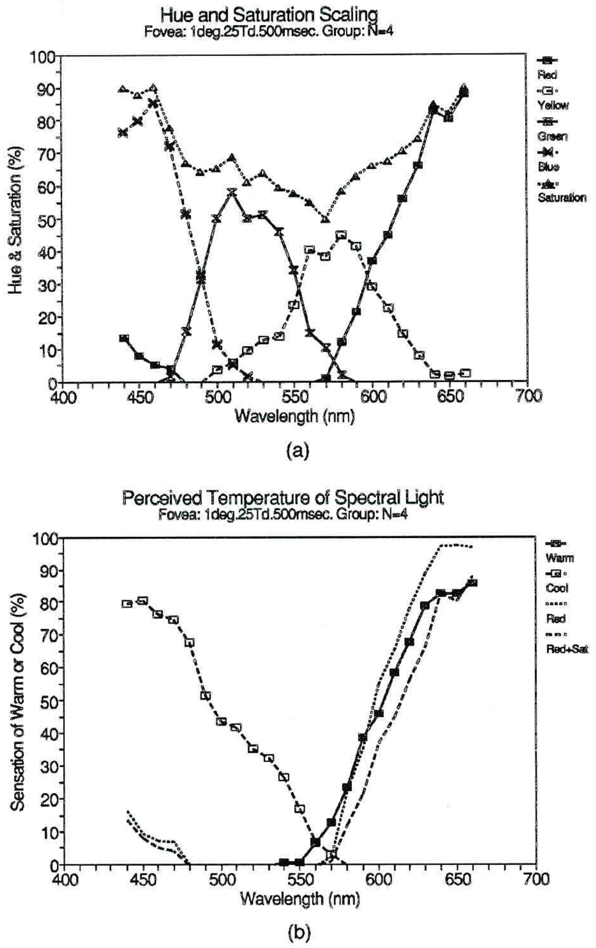


Fig. 4. Perceived temperature of flashes of monochromatic lights equated for luminance. Observers rated each flash as warm or cool using percentage scales. Mean ratings are given for a group of four observers. Dotted boundaries on either side of each curve are ±1 group standard error of the mean.



(a)

(b)

Fig. 5. (a) Hue and saturation scaling of flashes of monochromatic lights equated for luminance. Observers rated the percentages of red, yellow, green, and blue in their sensations, as well as saturation. Hue data have been rescaled so that the sum of the hues equals the saturation for each light. Same observers as for Fig. 4. (b) Perceived temperature data from Fig. 4 together with perceived redness data from Fig. 5(a). The "Red + Sat" curve is exactly as in Fig. 5(a); the "Red" curve has been rescaled at each wavelength to remove the saturation function.

minish as redness reappears ("violet"). The correlation of warmth and red holds even when the stimulus appears quite desaturated, as is the case when wavelengths are in the vicinity of 580 nm. It is worth noting that both redness and warmth disappear in the spectral region that corresponds to a unique sensation of yellow.

4. DISCUSSION

Observers can reliably adjust illumination to find a light that appears neither warm nor cool. Over the range from 50 to 2000 lux the chosen color temperature remains the same, at approximately 3700 K. The stability with illuminance is contrary to the widely accepted Kruithof functions[2]; those functions showed a range of 2200–2500 K at 50 lux, increasing to a range from 3500 to more than 10,000 K at 2000 lux. Not only do we not find a shift in central tendency with illuminance, but we also do not find any increase in the temperature-neutral range as illuminance increases.

Our value of 3700 K for temperature neutrality agrees well with our previous study on the illuminant that observers prefer for looking at artworks, approximately 3600 K.[5] That study used fixed, and rather large, steps in color temperature and did not vary intensity but did cover a much wider range of color temperatures (2500–7000 K); it also included a large variety of paintings encompassing a large color gamut. Informal observations and a recent pilot study with the adjustable lights described here suggest that the preferred illuminant for viewing works of art is closer to 3700 K across a range of intensities.[11] The observation that the illuminant that is neither warm nor cool seems to be the one preferred for looking at artworks leaves the question of why this is preferred. One might have expected that observers would have preferred lighting that was achromatic and that faithfully reproduced the reflectances of the objects being viewed. Clearly, however, we do not find this. In agreement with our findings, it has been reported that a light of color temperature close to 3700 K is far from achromatic; it is clearly yellowish, whereas achromatic lights are between 5000 and 6000 K over intensity ranges comparable to the ones we used.[12]

Color vision is robust when objects are illuminated by different broadband sources (color constancy), provided that color temperatures do not vary grossly.[13] In this vein, our previous work showed that preadaptation to various illuminants (2800–5800 K) had no effect on choice of the preferred illuminant for viewing museum displays.[5] However, despite the stability of color appearance over a wide range of illuminants, our observers clearly preferred a very specific color temperature for use in museums. This color temperature is one that appears neither warm nor cool. The value is set quite precisely, even though observers might have been adapting to the illuminant changes from adjustment to adjustment. The mystery is why observers prefer very specific illuminants even when color appearance would remain largely unchanged over a wider range of illuminants. Equally mysterious are the concordances between preferred museum illuminant, perceived temperature, and the spectral boundary of the sensory category of redness. Perhaps Kruithof's[2] hypothesis is correct that there is something desirable about lighting that appears temperature-neutral, although, as we have shown here, his finding of change in the warm–cool boundary is incorrect.

ACKNOWLEDGMENTS

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