LBL-25174
Preprint

Submitted to Lighting Research and Technology

Photopic Luminance Does Not Always Predict Perceived Room Brightness

S.M. Berman, D.L. Jewett, G. Fein,
G. Saika, and F. Ashford

August 1989

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

Published in Lighting Research and Technology,
Vol. 22, No. 1, pp. 37-41. Great Britain, 1990.

LBL-25174
L-139

PHOTOPIC LUMINANCE DOES NOT ALWAYS PREDICT PERCEIVED ROOM BRIGHTNESS

S M Berman† PhD, D L Jewett‡ MD, DPhil, G Fein‡ PhD,
G Saika‡ BS, F Ashford‡ BS

†Applied Science Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

‡University of California
School of Medicine
San Francisco, California 94143

August 1989

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-ACO3-76SFOOO98.

PHOTOPIC LUMINANCE DOES NOT ALWAYS PREDICT PERCEIVED ROOM BRIGHTNESS

Summary

The perception of room brightness over photopic luminances ranging from 30 cd/m^2 to 67 cd/m^2 was judged by 12 subjects in an almost uniformly white experimental chamber. Two different illuminants were compared which had different spectral compositions, but were color matched. Brightness judgements were often opposite to large differences in photopic luminance. These results are inconsistent with models of brightness perception that depend solely on cone receptors. At the luminance levels considered here subjective evaluation of light intensity depends upon both photopic and scotopic spectral contributions. These results imply that aspects of the visual system operate mesopically under most interior lighting conditions.

1. Introduction

The opponent model of color vision states that differences in wave length sensitivity between brightness perception and luminance arise because brightness depends on both color and achromatic channels, while luminance depends solely on the achromatic channel representing the sum of inputs from the cone photopigments.[1,2,3] Large contributions of chromatic channels to brightness perception are shown clearly by the work of Burns[4] and Alman et al,[5] who studied small (2°) fields of view. With a larger field of view (10°) Sanders and Wyszecki[6] found different values for the relationship between brightness perception and luminance. Palmer[7,8] studied large (45°) field photometry and found still different values relating brightness perception to luminance. This work is difficult to directly compare with the small field results because of the much lower photopic light levels and a failure to maintain constant perceived color. Thus, there has not been adequate measurements of brightness perception for full field of view and light levels typically used in the interior environment.

In the study described here, we show under such conditions that brightness perception of indirect lighting provided by two spectrally different but equal color (faintly - yellowish white in color) light sources can be paradoxically opposite to their photopic luminances. This large effect is incompatible with the opponent model of color vision wherein brightness perception depends solely on cone contributions.[1,2,3]

2. Methods

Twelve healthy adult paid volunteers (5 males and 7 females), 17 to 25 years of age participated in this study. All had visual acuities of at least 20/20 on the Snellen near vision acuity test and their color vision was normal on the Ishihara Test of Color Blindness. All subjects reported themselves to be free of drugs, and they denied hypersensitivity to light.

Testing took place in a sound-attenuating, RF-shielded chamber (Erik A. Lindgren & Associates, Chicago, IL) that measured 2.3 m high by 2 m by 2 m, whose insides were coated with Kodak (spectrally flat) reflective paint. We verified the spectral reflectance quality of the paint by measuring the spectral power distribution of the various fluorescent lamps used in the experiment by direct view of the lamp and indirectly by viewing the lit area on the front wall as seen by subjects. These two procedures yielded almost equal spectral power distributions. As a measure of the difference between the direct and reflected spectral distributions the photopic and scotopic luminances were determined under both conditions and they agreed within 2%. This small discrepancy was due to the inability of the instrument used (Spectra Pritchard photometer model 1980 A-86) to record the minute energy in the far tails of the lamp spectral distributions when the wall was viewed, while for the direct view of the lamps the power level was sufficient to provide a complete range of measured values.

The subjects sat in a chair and faced the coated metal wall which had few visual features, was about 1.1 m distant, and was bathed by light provided by combinations of fluorescent lamps, all of which were contained in a single fixture that was mounted above the subject's head shielded from the subject's direct view (see Figure 1). The rest of the chamber was lit by indirect light reflected primarily from the walls and ceiling. The luminance distribution on the viewed wall was approximately constant in the horizontal direction and varied by about 15% from ceiling to floor.

Four different comparisons of lighting conditions were tested. Three of the comparisons used the same pair of equal chromaticity illuminants (see Tables 1 and 2), approximately white in color, that were created by combinations of fluorescent lamps. One of the combination illuminants, referred to as WWG, consisted of a single warm white fluorescent lamp combined with a single gold fluorescent lamp. The other combination illuminant, referred to as R213, consisted of three red fluorescent lamps combined with a special fluorescent lamp using Sylvania Phosphor #213, a phosphor used in photocopy lamps. The '213' lamp phosphor produces a greenish-blue visible light whose spectrum is peaked at 505 nm, and is about 20 nm wide. All lamps were standard F40 T-12 tubes, i.e., 40 watt, 38 mm diameter, and 1 m in length. Lamp lumen outputs were varied using dimming electronic ballasts.

The photopic luminances of each of the individual lamps that comprised the comparison illuminants for the brightness comparisons were determined in two stages. The first stage consisted of adjusting the individual luminances, so that the illuminant combinations WWG and R213 had the same 10° chromaticities. Because of the full field of view used in our experiments, a second stage of adjustment was required which involved interactive feedback from the subjects and is discussed below. Measurements of the individual lamp spectral power distributions were made using a Spectra Pritchard photometer (model 1980 A-PL), with aperture setting of 6 minutes of arc, that viewed the area on the chamber wall directly in front of the subjects. All luminances were measured at this same spot on the wall with the same photometer aperture. Calculations of the chromaticities of each lamp were based on 10° supplemental observer tristimulus values[9]. Since the judgements of brightness by our subjects were made with a full field of view, it would have been preferable to use tristimulus values for a much larger viewing angle than the supplemental observer, but to our knowledge there is no data published for viewing angles greater than 10°.[10] Table 1 lists the individual (x, y) chromaticities, based on the supplemental 10° observer, of the four lamp types used in this study.

Figure 2 shows the (x,y) chromaticity diagram with the four individual lamp types indicated and plotted using the 10° supplemental observer tristimulus values. A mixture of luminances from two lamps will fall on a line defined by their individual chromaticity points with the location of the point on the line being proportional to the ratio of the constituent luminances. From Figure 2, it can be seen that warm white and gold lamps can be combined to have the same chromaticity as a combination of the red and '213' lamp, i.e., at the point of intersection of the two straight lines defined by the two constituents of the combination lamps.

If (x_m, y_m) are the chromaticities of the equal color combination, i.e., the point of intersection, then the ratio of values of the photopic luminances of the constituent lamps P_1/P_2 is determined from the condition that each of the tristimulus values of the combination source be equal to the sum of the tristimulus values of its constituents. This leads to the equation for that ratio as:

$$P_1 / P_2 = \left(\frac{y_1}{y_2}\right)\left(\frac{y_2 - y_m}{y_m - y_1}\right)$$

where y_1 and y_2 are the y chromaticities of the constituent lamps. The chromaticity coordinates of the intersection point of the two lines for the combination lamps x_m and y_m, are presented in Table 1 as the calculated predicted metameric lights. For any given pair of illuminants, the total luminance for the pair could be adjusted while keeping constant the ratio of the luminances of the constituents of the pair, as given in the above equation.

When the chamber walls were lit by the combination illuminants with the luminances of the constituent lights determined by the above equation, subjects perceived a slight color difference. The WWG combination appeared more yellow than the R213 at equal photopic luminance. This necessitated the second stage of ratio adjustment to generate a better color match. The experimenter adjusted the luminances of the constituent lamps, keeping the total photopic luminance of each pair constant at 50 cd/m^2, with interactive feedback from the subject, until no further improvement in color match was obtained. The procedure was followed for four subjects, each yielding quite similar settings for the constituents of the comparison pairs. The mean values of the chromaticities are presented at the bottom of Table 1, and these values were then used for all subjects.

The adjustments, described above, of the relative luminances of the constituent lamps within each combination illuminant resulted in a separation of the combination illuminants on the 10 degree supplemental observer chromaticity plots. If this separation created a difference in chromaticity of the two combination illuminants, it would introduce a bias towards judging the combination illuminant with greater chromaticity relative to achromatic white as brighter.(9) In the discussion section, after the results of the brightness judgements have been presented, we will argue that any bias related to chromaticity differences between the combination illuminants would be an order of magnitude smaller than the experimental differences obtained here.

The brightness comparisons between two lighting conditions were made in the following manner. Subjects were adapted to the room which was lit by the WWG illuminant with luminance set at 36 cd/m^2 for 15 minutes before any testing. To reduce boredom, the subjects viewed a grade B movie before and between testing on a 7.6 cm black and white television screen that was approximately 40 cm away and directly in front of the subject at eye level. The TV had a liquid crystal display, i.e., it was not self luminous but was lit only by the ambient illumination. During testing the subjects looked away from the TV and fixated on an area of illuminated wall which they faced i.e., the area measured by the photometer. For each comparison between illuminants, each subject made 10 choices. For each choice, the subject was presented with three alternations between the two equal color comparison illuminants and then was asked to report under which lighting condition the room appeared brighter. The order of the illuminants was randomly assigned and each illuminant was presented for approximately 5 seconds, resulting in a sequence of three pairs of uninterrupted 5 second periods. The two illuminants being compared were identified by the experimenter to the subjects by giving the lighting condition a random number and the subjects were informed of each presentation by intercom being told e.g., "here is number 6, here is number 17," repeated three times. The question was then asked "which one appeared brighter?" The last presentation remained on while the question was asked and until the next sequence began approximately 30 seconds later. Using a photo-diode we determined that the switching between illuminants occurred within 100 ms, with no more than 25 ms of dimness, and at no time were both of the equal color combination illuminants on simultaneously.

The four pairs of luminance conditions studied are shown in Table 2. Comparisons 1, 2, and 3 involved the color-matched pairs, while comparison 4 used only a single light source (i.e., warm-white fluorescent). The choice of maximum luminance was dictated in part by the maximum possible output of the bank of red fluorescent lamps. The net R213 combination luminance of 50 cd/m^2 for comparison 2, is based on the maximum output from the 3 red fluorescent lamps. The values for comparison 1 were chosen so that a test could be made at at least two typical interior light levels. Comparison 4 compares two luminance levels of the same lamp with the percentage difference in photopic luminance approximately the same as in comparisons 1 and 2. This comparison was used to demonstrate that, with this experimental paradigm, the values chosen for comparisons 1, 2 and 3 are above the difference limen.

3. Results

Table 3 shows for each comparison, the number of times each subject chose each lighting condition as the brighter.

The brightness judgements for comparison 4 were highly consistent, with the 52 cd/m^2 presentation judged brighter than the 40 cd/m^2 presentation on 115 out of 120 paired comparisons. Thus, the luminance differences studied here are clearly above the difference limen for brightness judgements made under our experimental conditions.

Comparison 1 produced the paradoxical result that 10 of 12 subjects judge as brighter the equal color illuminant that is 33% photopically dimmer (R213). Similar results for 9 of 12 subjects are obtained in comparison 2, where the luminance is larger than in comparison 1, but the ratio of the photopic luminance of the two illuminants is the same as in comparison 1.

Statistical Analysis

The null hypothesis tested was that judgements of relative brightness of the color matched illuminants were based on photopic luminances. Thus, since the ratios of photopic luminances between the illuminant pairs were the same in comparisons 1, 2, and 4, the null hypothesis to be tested was that the brightness judgements would be the same for comparisons 1, 2, and 4. The sample size was 12 subjects; for each subject the 10 judgements for each comparison yielded a judgement score ranging from 0 to 10. These scores were used as our measure of the degree to which the subject consistently judged one illuminant to be brighter than the other. The distribution of judgement scores was clustered around 10 or 0, i.e., was highly non-normal for all four comparisons, with most judgement scores (33 out of 48) at 0 or 10 and none at 4-6 (near chance judgement of one light brighter than the other). We tested the null hypothesis separately contrasting comparison 1 with comparison 4, and comparison 2 with comparison 4 using the Wilcoxon Signed-Ranks Test.(11) We computed the exact Wilcoxon probability rather than its normal approximation, because of the relatively small sample size, the non-normal distribution of judgement scores, and because there were many cases with equal differences between judgment scores. Using a two-tail test, the null hypothesis was rejected in both cases. Contrasting comparison 1 with comparison 4, $p = .002$; while contrasting comparison 2 with comparison 4, $p = .001$.

In both comparisons 1 and 2, the R213 combination had greater scotopic luminance than did the WWG, suggesting that scotopic luminance was the predominant factor in brightness judgements. If scotopic luminance were the only factor, then the potentially metameric sources should appear equally bright when the scotopic luminances were equal. However, comparison 3 shows that scotopic luminance does not fully account for brightness judgements, since the WWG was chosen as brighter (116 of 120 times), even though it had a lower scotopic luminance than the R213 (WWG-57 scd/m^2; R213-72 scd/m^2; Table 2). We conclude that, in these conditions neither scotopic nor photopic luminance alone accounts for perceived brightness.

4. Discussion

Under the color matched lighting conditions of comparisons 1 and 2, (full field of view and alternation of lighting condition at 5 second intervals), subjective brightness judgements were, opposite to what would be expected if they were a direct consequence of photopic luminance. This effect was large, with over 3/4 of the subjects judging the photopically less intense illuminant as consistently brighter than the photopically more intense illuminant (i.e., 33 percent greater photopic luminance). For comparisons 1 and 2, the average brightness judgement was consistent with the 112 percent difference in scotopic luminance (Tables 2 and 3). This result is consistent with findings on brightness judgements by a submarine crew.[12] When the submarine was relamped with lighting of slightly less photopic illumination, but with higher scotopic illumination the crew strongly indicated the replacement lighting appeared brighter.

In comparison 3, where the WWG luminance from comparison 2 was judged against the R213 luminance from comparison 1, all subjects consistently chose the WWG as brighter (Table 3). Since, in comparison 3, the R213 was still 28 percent more intense scotopically than the WWG, the brightness judgement could not have been solely determined by the scotopic luminance. Thus, brightness as judged under our experimental conditions is not a unique function of either photopic or scotopic luminance.† As noted in the methods section, we made

† From the results of comparisons 1 and 3, we know that the level of luminance of the WWG illuminant that would provide a brightness match with the value of 30 photopic cd/m^2 of the equal color illuminant R213 lies between 40 cd/m^2 and 67 cd/m^2. Because of the difficulty for naive subjects to be able to judge a brightness match we have not attempted to determine the exact brightness equality condition. In the absence of this information we have made a crude estimate of the brightness match value by extrapolating the present data using an ad hoc model of brightness dependence on stimulus strength: B = log P + ´ log S, where B is the brightness and P, S are photopic and scotopic luminances and ´ is a constant which indexes the relative contribution of scotopic luminance to brightness perception at these light levels. By linear extrapolation between the conditions of comparison 1 where only 2 out of 12 subjects reported the WWG of 40 cd/m^2 as brighter and comparison 3 where 12 out of 12 subjects reported the WWG of 67 cd/m^2 as brighter we can find the value of log P (or P) where 6 out of 12 subjects would report the WWG as brighter. Using this procedure, brightness equality occurs at 49 cd/m^2 for the WWG illuminant when compared to 30 cd/m^2 for the R213 a value more than 50% greater and in addition yields ´ = .91.

adjustments to the luminances of the constituent lights in each combination illuminant to make the combination illuminants more closely color matched. These adjustments resulted in a separation of the combination illuminants on the 10 degree supplemental observer chromaticity plots. If this separation created a difference in chromaticity of the two combination illuminants, it would introduce a bias towards judging the combination illuminant with greater chromaticity as brighter. Ratios of brightness to luminance for 10 degree fields have been reported for chromaticity values close to those of the combination illuminants we used. These ratios are reported to differ by only two percent(9) for chromaticity coordinates very close to those of our R213 and WWG combination illuminants, i.e., compare R213 (.460, 419) WWG (.479, .406) with the 2 percent perceived difference(9) between (.473, .413) and (.436, .399). The brightness judgements we observed are opposite to a 33 percent difference in photopic luminance; it is unlikely for this to be a consequence of the small differences in brightness perception which might result from the chromaticity separation (based on the 10 degree observer) of our combination illuminants. Since equal chromaticity and photopic luminance gives equal excitation of the cone receptors, our results on brightness judgement cannot be solely due to cone receptors; hence rod receptors must be active at these light levels. Rod activity at these luminance levels is supported by the results of Stiles and Wyszecki,(13) who found that luminances as high as 30,000 cd/m^2 are required to assure absence of rod effects in large field color matching experiments. These results taken together with our previous findings,(14) that pupil size for large viewing fields is largely a function of the scotopic spectrum, implies that aspects of the mesopic region of vision apply to most interior lighting conditions.

Luminance levels used were those commonly encountered in the interior lighting environment. Since there are substantial differences in spectral distributions of commonly used lamps (incandescent, fluorescent, high pressure sodium, metal halide) their spectral effects should be considered when evaluating or designing lighting environments for human habitation.

Acknowledgement

We thank Francis Rubinstein and Daniel Greenhouse for assistance in photometric measurements, Larry Bingham for his help in subject protocol and early data analysis and Oliver Morse for electronics support. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-ACO3-76SFOOO98.

References

1 Guth S L and Lodge H R Heterochromatic additivity foveal spectral intensity and a new color model Journal of the Optical Society of America **63** 450-462 (1973)

2 DeValois R and DeValois K K Neural coding of color Handbook of Perception **5** (1975)

3 Howett G L The coming redefinition of photometry Journal of the Illuminating Engineering Society **15** 5-18 (1986)

4 Burns S A Smith V C Porkorny J and Eisner A E Brightness of equal-luminance lights Journal of the Optical Society of America **72** 1225-1231 (1982)

5 Alman D H Breton M E and Barbour J New results on the brightness matching of heterochromatic stimuli Journal of the Illuminating Engineering Society **12** 268-274 (1983)

6 Sanders C L and Wyszecki G Correlate for brightness in terms of CIE color matching data Paper P-636 CIE Central Bureau Paris See also Wyszecki and Stiles Optical Citation 412 (1964)

7 Palmer D A The definition of a standard observer for mesopic photometry Vision Research **7** 619-628 (1967)

8 Palmer D A Standard observer for large field photometry at any level Journal of the Optical Society of America **58** 1296-1129 (1968)

9 Wyszecki G and Stiles W S Color science 2nd edition Wiley NY (1982)

10 Trezona P W Additivity in the tetachromatic colour matching system Vision Research **14** 1291-1303 (1974)

11 Siegel S Non parametric statistics for the behavioral sciences McGraw-Hill NY (1956)

12 Luria S M Effects of full spectrum lighting on submarines Naval Submarine Medical Laboratory **1092** (1987)

13 Stiles W S and Wyszecki G Rod intrusion in large-field color matching Acta Chromatica **2** 155-163 (1973)

14 Berman S M Jewett D J Bingham L R Nahass R M Perry F and Fein G Pupillary size differences under incandescent and high pressure sodium lamps Journal of the Illuminating Engineering Society **16** 3-20 (1987)

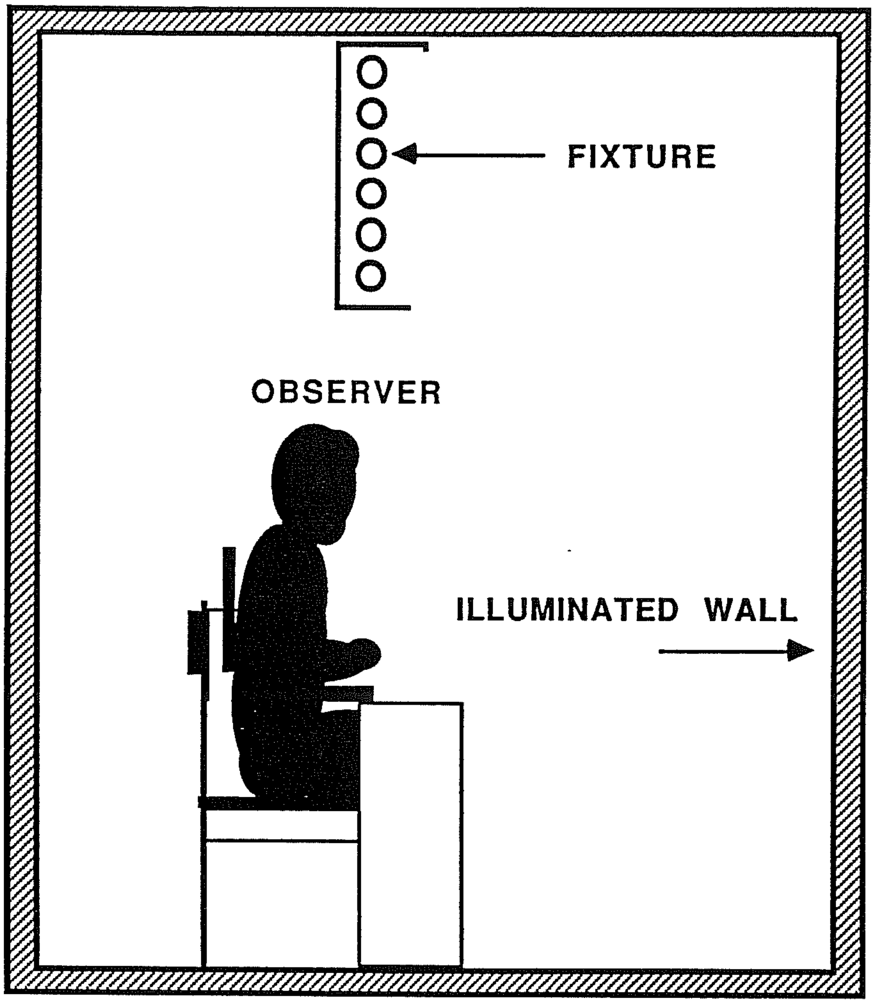
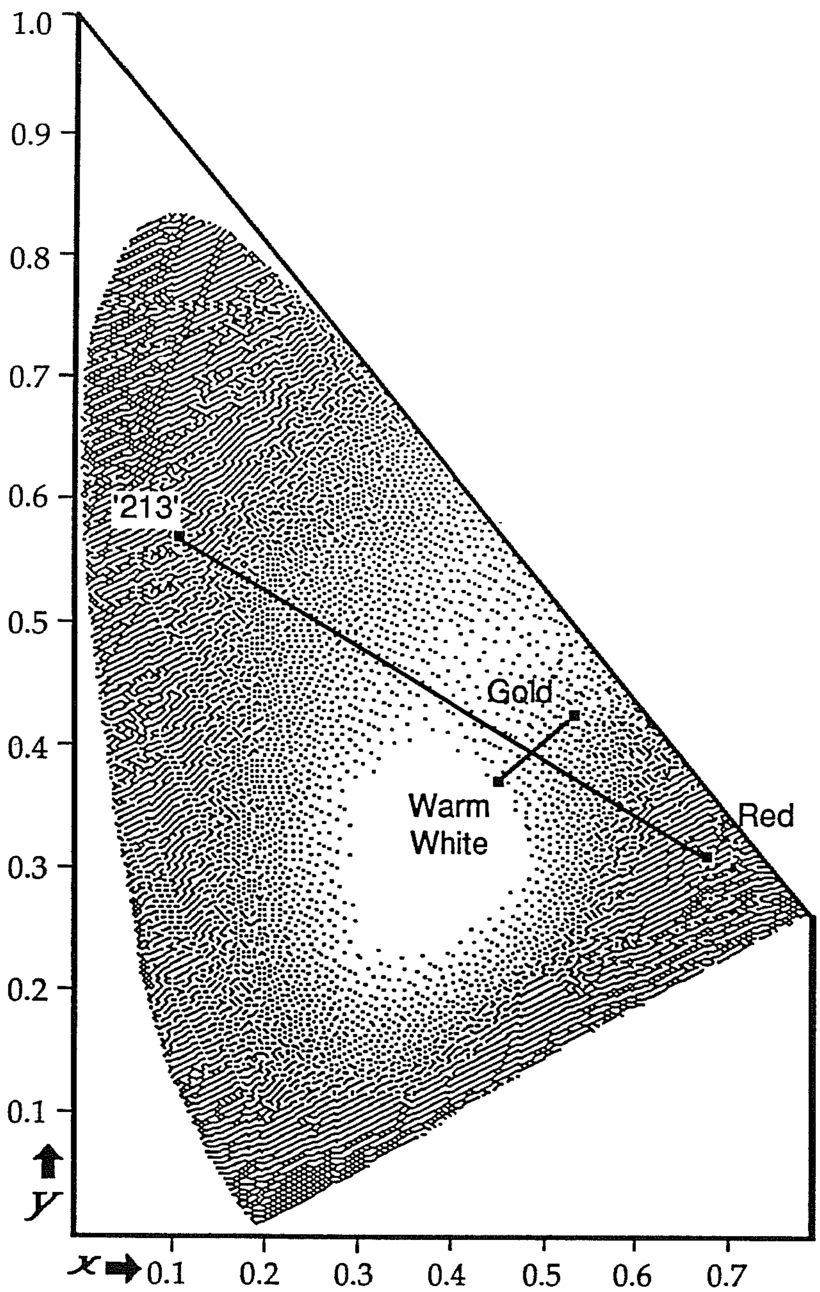


Figure 1: Cross sectional sketch of chamber.



XBL 8810-3556

Figure 2: Chromaticity diagram displaying the individual chromaticities of the comparison pairs. The red and '213' lamps are combined so that their net chromaticity has the same value as the combination of the warm white and gold pair. The equation for the luminance ratio to achieve a given chromaticity is given in the text. The increased hatching is to indicate a higher level of color purity.

TABLE 1: Chromaticity coordinates of the individual lamps and potentially metameric conditions

	X	Y
Warm White	.4565	.3869
Gold	.5406	.4573
Red	.6858	.3138
'213'	.1332	.5714
Calculated Predicted Metameric	.4824	.4086
Coordinates that provided best subjective color match	.460 (R213) .479 (WWG)	.419 (R213) .406 (WWG)

TABLE 2: Lighting conditions for the brightness comparisons

Lighting Conditions	Comparison 1 WWG/R213	Comparison 2 WWG/R213	Comparison 3 WWG/R213	Comparison 4 WW/WW
Photopic Luminance cd/m^2	40 | 30	67 | 50	67 | 30	52 | 40
Luminance Ratio (Higher/Lower)	1.3	1.3	2.2	1.3
Scotopic Luminance cd/m^2	34 | 73	57 | 121	57 | 73	50 | 39
Luminance Ratio (Higher/Lower)	2.1	2.1	1.3	1.3

TABLE 3: Number of times subject chose the given condition as brighter (luminances are given in Table 2).

Brightness Judgements	Comparison 1 WWG/R213		Comparison 2 WWG/R213		Comparison 3 WWG/R213		Comparison 4 WW/WW	
Subject 1	0	10	0	10	10	0	10	0
Subject 2	10	0	9	1	10	0	10	0
Subject 3	0	10	1	9	9	1	7	3
Subject 4	0	10	0	10	10	0	10	0
Subject 5	0	10	0	10	10	0	10	0
Subject 6	2	8	10	0	9	1	9	1
Subject 7	1	9	3	7	10	0	10	0
Subject 8	1	9	0	10	9	1	10	0
Subject 9	10	0	9	1	10	0	10	0
Subject 10	0	10	2	8	9	1	9	1
Subject 11	0	10	0	10	10	0	10	0
Subject 12	0	10	0	10	10	0	10	0
TOTALS	24	96	34	86	116	4	115	5