Color and brightness discrimination of white LEDs

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Abstract

Great strides have recently been made in the development of white light emitting diodes (LEDs), although perceptible variations remain in the color and brightness of nominally identical products. The objective of this study was to examine color and brightness discriminability between different white LEDs when used as illuminants of colored and achromatic objects. A method of successive comparisons was used to assess discriminability rather than the more typical simultaneous (side-by-side) comparisons using a "same-different" response protocol. Three-dimensional "tolerance zones" were developed based upon discriminability in chromaticity (u', v') and luminance when illuminating the colored and achromatic objects. These "tolerance zones" could be used to establish specification tolerances for different lighting applications.
Keywords: chromaticity, discrimination, LED, luminance, white light LED, tolerance zones

1.0 Introduction

To a greater degree than any other light source, white light emitting diodes (LEDs) exhibit variations in chromaticity and luminance within the same manufacturing batch. To assess these variations physical measurements of luminance and chromaticity (u', v') were obtained from a large sample of white LEDs. The degree to which these variations matter in different lighting applications will depend upon the degree to which these variations produce perceptible differences when they are used as illuminants for colored and achromatic objects. The main goal of this study was to develop three-dimensional "tolerance zones" (chromaticity and luminance) from controlled psychophysical experiments. One psychophysical experiment examined perceived differences in color for different white LEDs of the same luminance; a second experiment examined perceived differences in brightness for the same white LED operated at different luminances. It is envisioned that the "tolerance zones" developed from the psychophysical data could be used as specification criteria for maintaining consistent chromaticities and luminances of white LEDs for applications where they might be used to illuminate colored and achromatic objects.

2.0 Methods

2.1 Apparatus

An apparatus (Figure 1) was designed to characterize the chromaticities and luminances of fifty white LEDs and to conduct two psychophysical experiments using a smaller sample of these LEDs. The experiments were designed to assess discriminable differences between the perceived colors (the chromaticity experiment) and brightnesses (the luminance experiment) of LEDs using a temporal, or successive-presentation, psychophysical procedure. All measurements were obtained in a black laboratory space at the Lighting Research Center.

The inside of an integrating sphere, 20 cm diameter, was painted with white, barium-sulfate paint. Twelve 5 mm ports were drilled along the seam of one hemisphere to house individual white LEDs. Another hole was drilled into the sphere to accommodate a small photodiode that served to monitor light output from the white LEDs; the photodiode was shielded from direct illumination from any LED. Two 5 cm diameter apertures were cut into the sphere directly opposite each other; one aperture served as the monocular viewing/measurement port and the other accommodated presentation of two-dimensional colored and achromatic objects during the psychophysical experiments. Energizing any one of the twelve white LEDs positioned in their respective holes provided uniform illumination on a two-dimensional object positioned in the presentation port.

For the psychophysical experiments, a two-lens optical system, a 50 mm camera (f/1.8 AF Nikkor) lens and a multi-element, wide-angle eyepiece with an effective focal length of 25 mm (Edmund Industrial Optics), was positioned in front of the viewing port to magnify the image of the colored or achromatic test objects located in the presentation port. The eyepiece was fitted with a circular metal baffle to frame the image of the test object. The two-lens system provided a 3.5 magnification of the test object with an exit pupil that overfilled the subjects' natural pupil sizes. Therefore the apparent luminance was equal to the measured luminance of the test object minus an estimated 5% lens transmittance loss. The two-lens system was removed for chromaticity and luminance measurements.

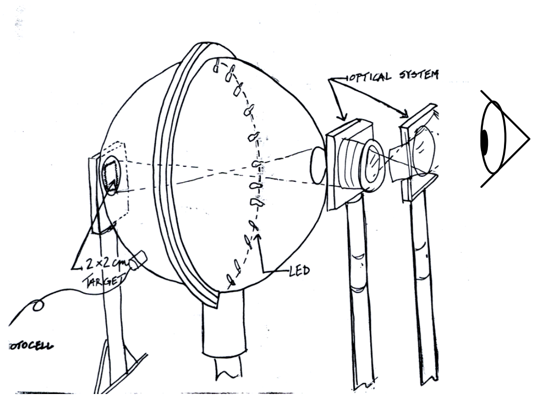

Figure 1: Experimental apparatus providing uniform illumination from one of twelve white LEDs on a two-dimensional test object positioned on one side of the sphere and viewed from the opposite side through a magnifying (3.5x) lens system.

2.2 Calibration

Fifty high-brightness, 5 mm, white LEDs manufactured by Nichia America Corporation were obtained in one batch for possible use in the psychophysical experiments (Figure 2). Every LED was tested in the sphere by inserting it into one of the twelve holes. All fifty LEDs were controlled to produce approximately 42 cd/m^2 from the inside wall of the integrating sphere while chromaticity measurements were made with a spectroradiometer (Photo Research PR705). LED drive currents were between 50 and 60 mA.

During the psychophysical experiments a feedback system using the photodiode adjusted the LED drive current to maintain a constant luminous output. Measurements were made at the viewing port with fast response measurement systems (LMT, Model PS0SCO; Oriel (Instaspec IV) CCD, Model 77131 and Oriel Spectrograph, Model 77400) to ensure constant luminance and chromaticity of the sphere wall for the briefly energized LEDs used in the psychophysical experiments. The luminous output of every LED was precisely controlled to within 1%, regardless of local temperature, using the feedback system and a customized LabVIEW program. Chromaticity values were within one MacAdam ellipse[1] throughout the duration of the presentation periods (1 to 3 s).

Twelve LEDs were selected for the chromaticity experiment (Figure 2). One LED served as the reference source; the other 11 LEDs were separated by approximately equal incremental distances in color space (u', v'). All LEDs produced 20 cd/m^2 on the inside surface of the integrating sphere during the chromaticity experiment. LED drive currents were approximately 27 mA. For the luminance experiment, only the reference LED from the chromaticity experiment was used. It produced eleven luminances in this experiment by operating it at different drive currents. The reference luminance was 20 cd/m^{2,} as in the chromaticity experiment; ten test luminances were employed varying from 15 to 19 cd/m^2 and from 21 to 25 cd/m^2 in 1cd/m^2 increments.

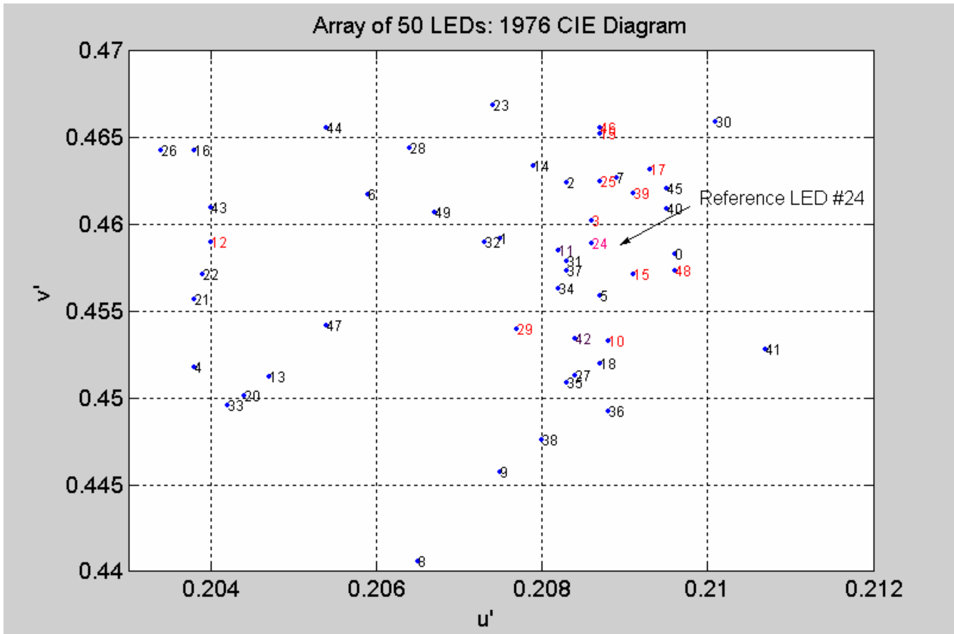

Figure 2: Chromaticity coordinates of 50 white LEDs from one batch, including the 12 selected for use in the psychophysical experiments. The chromaticity of the reference white LED is designated as #24.

2.3 Test objects

Three test objects were used as stimuli in the psychophysical experiment (Figure 3). One object was a uniform, white test card with a small dot located just above the center of the visual field to provide a fixation point. Two United States postage stamps were also used. One was a pale, monotone, magenta portrait of Virginia Apgar (23.8 by 20.6 mm) and the other was a vivid, multi-color rendering of a red apple with green leaves on a blue background (23.8 by 19.1 mm). When seen through the two-lens optical system, the stamps subtended visual angles of 15^{o} high and 13^{o} wide, and 15^{o} high and 12^{o} wide, respectively.

Figure3: Three test objects: a multi-color stamp, a monotone stamp and a white card with a fixation point.

2.4 Inter-stimulus intervals

LEDs successively illuminated the test objects during the psychophysical experiment. Four inter-stimulus intervals (ISI) were used, 0, 79, 319 and 639 ms, during which time no LEDs were energized.

2.5 Subjects
Four volunteers, one female and three males ranging in age from 23 to 35 years of age, were recruited from the staff of the Lighting Research Center and served in both experiments. They all had normal color vision using the standard Ishihara color-plate test and a minimum near-vision Snellen acuity of 20/25.

3.0 Procedures

Two psychophysical experiments were performed, one examined perceived differences between LEDs of different chromaticity and the other examined perceived differences in luminance of the same LED.

In both experiments, the subject was seated in front of the apparatus and viewed the test objects through the eyepiece with the right eye; the left eye was covered with an opaque patch. Before collecting data the subject was given time to adjust the height of the stool, position the chin in a rigid holder, and focus the two-lens optical system. Once comfortably and correctly located, the room lights were turned off and one LED was turned on so that the subject could adapt for approximately 10 s to the light levels used in the experiment.

The experiment was composed of three sessions per subject; one of the three test objects was presented during a given session. A program was developed that randomized the presentation order and ISI for a given session. In the chromaticity experiment the reference LED was always presented first for three seconds, followed by one of the four randomly selected ISIs and then followed by a one-second presentation of a randomly selected test LED, or a repeat presentation of the reference LED. Random selection was performed “without replacement” so that the reference LED was always compared to every combination of ISI and test LED, three times during a session. In addition, randomly inserted into the session, the reference LED was compared to itself six times for every ISI. A total of 156 trials were performed within a session in the chromaticity experiment. An identical procedure was used in the luminance experiment for a total of 144 trials per session.

Subjects were asked to respond “same” or “different” to the successive presentation. Presumably, the subjects had no cues on which to base their responses other than perceived differences in the colors or brightnesses of the test objects.

4.0 Results

4.1 Chromaticity experiment
The chromaticity experiment tested the impact of ISI, test object and chromaticity (incremental distance) at a luminance level of 20 cd/m^2 using “same-different” responses from four subjects. A repeated measures analysis of variance (ANOVA) showed main effects for test object ($p < 0.05$), and for incremental distance in u’,v’ space ($p < 0.0001$). No other main effects or interactions were significant. Discriminability was best (fewer “same” responses) for the white background and was poorest for the multi-color stamp (Figure 4). Paired t-tests showed significant differences between all test objects, white vs. monotone ($t = 4.790$, $p < 0.0001$), monotone vs. multi-color ($t = 2.946$, $p < 0.05$), and white vs. multi-color ($t = 7.340$, $p < 0.0001$).

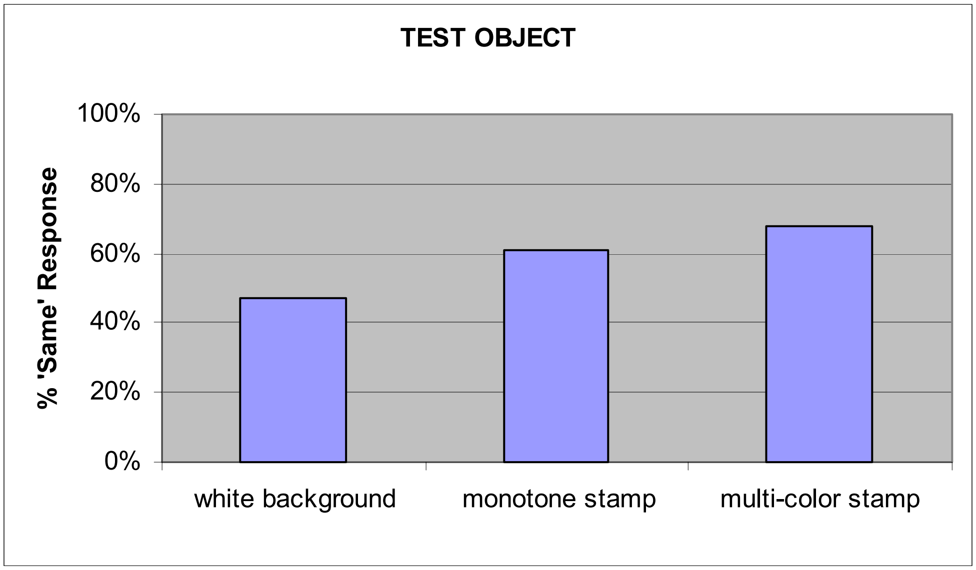

Figure 4: Discriminability between white LEDs was best for the white background and worst for the multi-color stamp. All backgrounds were significantly different from each other using post-hoc paired comparisons.

Discriminability increased as the incremental distance in chromaticity space (u',v') increased from the chromaticity of the reference white LED (Figure 5). A linear fit was applied to the data resulting in an R^2 of 0.94.

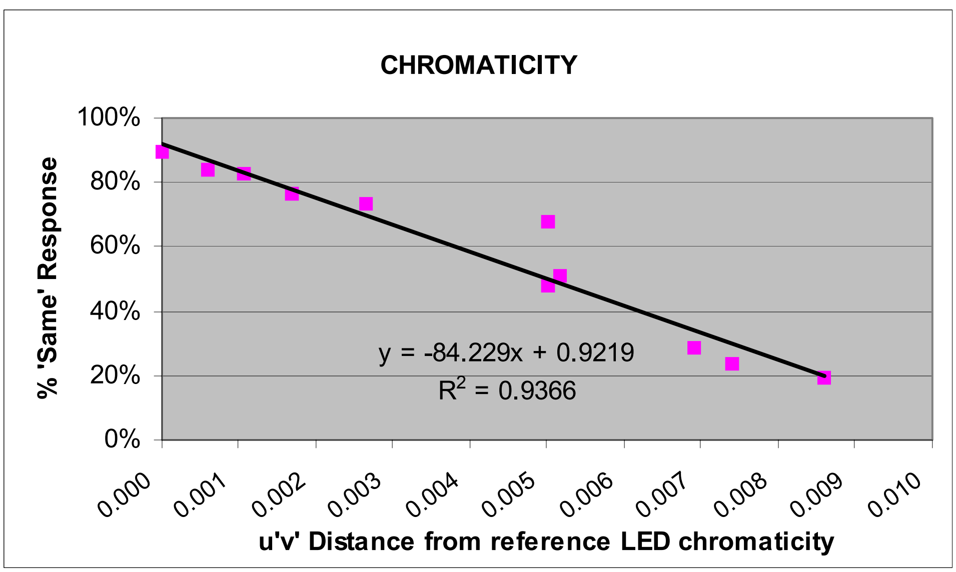

Figure 5: Discriminability increased linearly with incremental distance in chromaticity space.

4.2 Luminance experiment
The luminance experiment tested ISI, test object and luminance using the reference white LED in the first experiment. Repeated measures ANOVA showed a main effect for luminance ($p < 0.05$), and an interaction between luminance and ISI ($p < 0.0001$). No other main effects or interactions were significant.

Paired t-tests showed that the reference LED (20 cd/m^2) was significantly different than all test luminances of 18 cd/m^2 or lower and all test luminances of 23 cd/m^2 or higher. A second-order polynomial was fitted to the luminance data, resulting in an R^2 of 0.94.

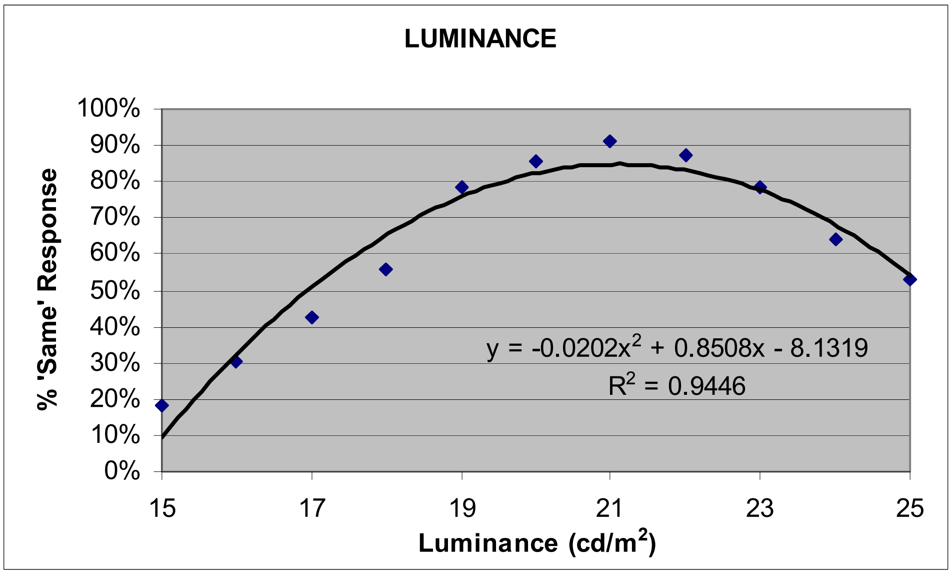

Figure 6: Discriminability was poorest near the luminance of reference LED (20 cd/m^2), increasing as test LED luminance increased and decreased.

The significant interaction between luminance and ISI is shown in Figure 7. It is clear from this figure that discriminability between the luminance of the reference LED and the test LEDs at the 0 ms ISI was different than discriminability between reference and test luminances at the other three ISIs. At test luminances higher than the reference LED, discriminability was essentially the same for the three longest ISIs, and consistently best for the 0 ms ISI. Further, the poorest discriminability at the 0 ms ISI was for a test luminance equal to the reference luminance, but the poorest discriminability was shifted to higher luminances for the other three ISIs, peaking at approximately 21 or 22 cd/m^2.

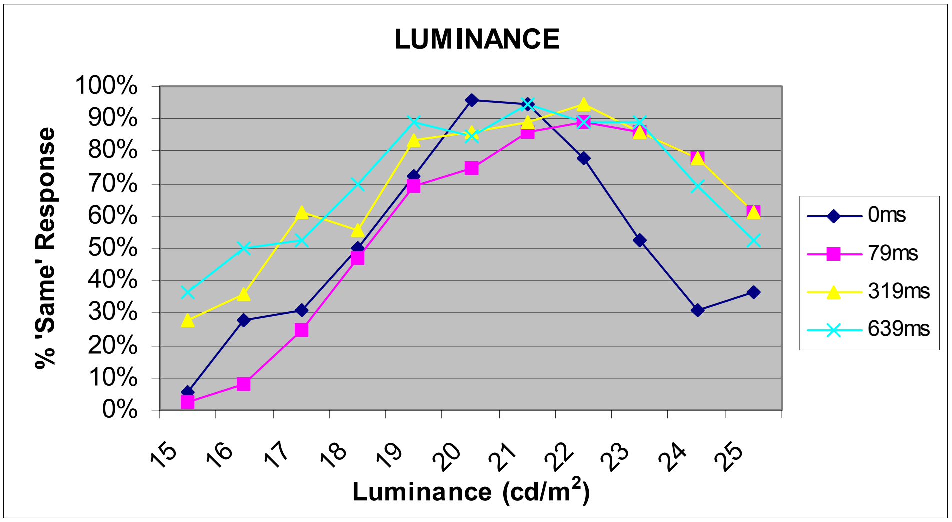

Figure 7: Discriminability between the reference light and test light was a function of both the luminance of the test light and the ISI

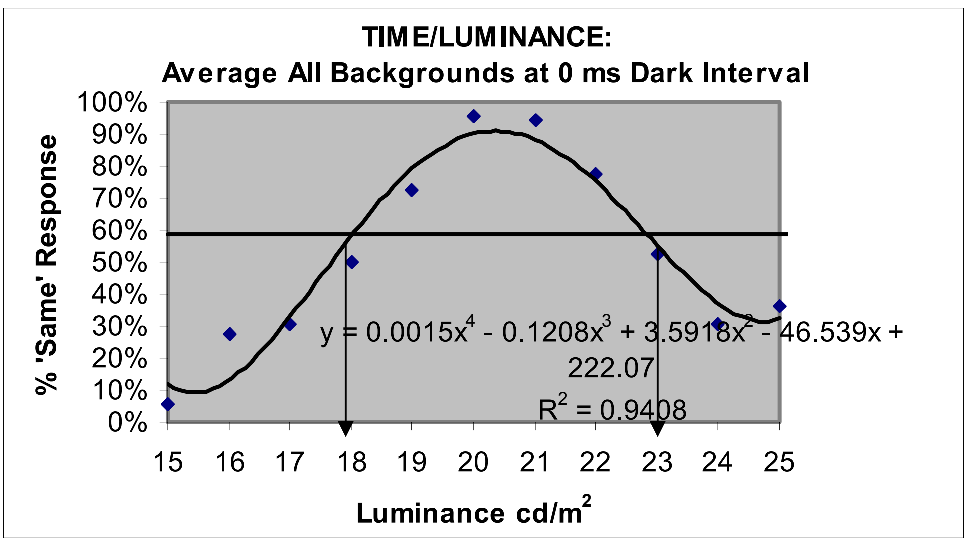

Figure 8: Discriminability data at the 0 ms ISI was fitted with a fourth-order polynomial and criterion values

4.3 Tolerance Zones

The goal of the study was to develop three-dimensional 'tolerance zones' that could be used as specification criteria for maintaining consistent chromaticities and luminances of white LEDs for applications where they might be used to illuminate colored and achromatic objects.

A fourth-order polynomial was fitted to the 0 ms ISI data from Figure 7 for interpolation purposes only (Figure 8). The 0 ms ISI was chosen for developing the luminance dimension of the tolerance zones because people would usually view multiple sources of white LED illumination simultaneously. A discriminability criterion of 58.5% "same" response was chosen because it was the mid-point between the probability of saying "same" when the reference LED was compared to itself (24 trials out of 156 in a session, or 17%), the chance hit rate, and the probability of always saying "same" for every presentation, the false positive rate plus the hit rate. This criterion intersected the fourth-order polynomial model at two luminances, one higher (22.87 cd/m^2) and one lower (18.01 cd/m^2) than the reference luminance. These two values served as the length of the luminance dimension of the tolerance zone. It should be noted that discriminability is better for decrements in luminance than for increments[2].

Since there was a significant difference between the three tests objects, but no interaction between test object and any other variable in the chromaticity experiment, three linear regressions were performed on the incremental distance data. As for the luminance of the tolerance zones, a criterion of 57.5% was used as the estimated distance in chromaticity space for each LED for the three tolerance zones. This criterion was the mid point between the chance hit rate and the hit rate plus false positive rate in the chromaticity experiment and resulted in incremental distances in chromaticity space of 0.0027, 0.0048, and 0.0053.

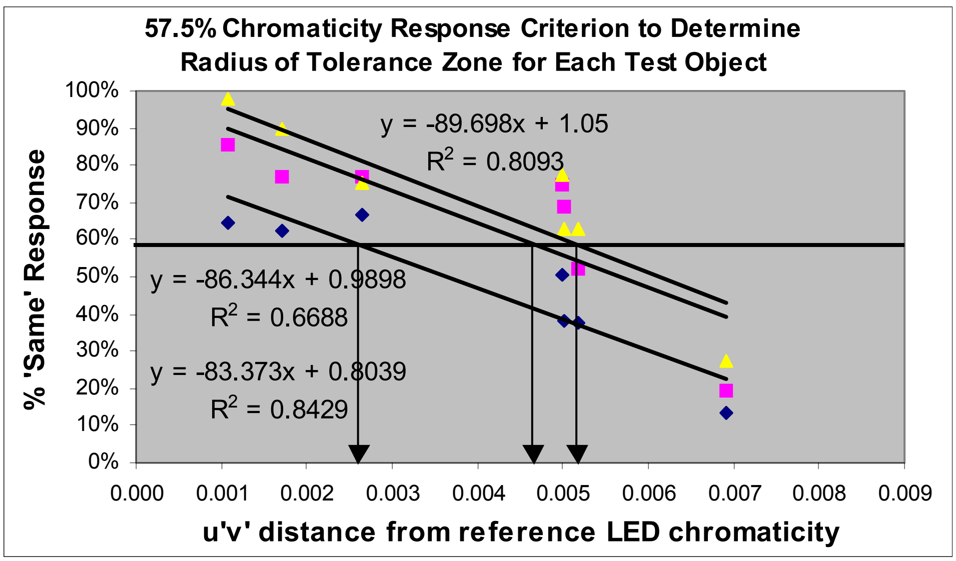

Figure 9: Discriminability data for the three test objects fitted with linear regressions and the criteria distances in u', v' color space from the chromaticity of the reference LED.

The values derived from Figure 9 can be translated into the circle radii in chromaticity space (Figure 10). The smallest radius, and therefore the best discriminability in color space, is associated with the white background. The largest radius is associated with the multi-color stamp.

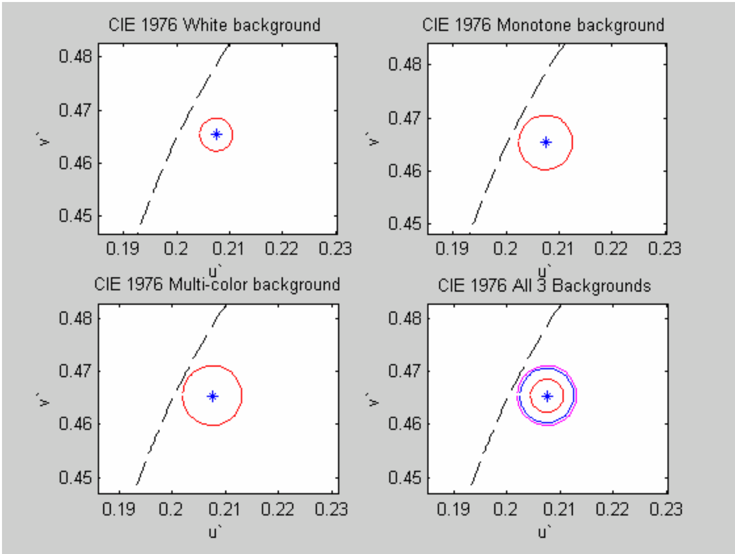

Figure 10. Constant criterion discriminability radii in u', v' color space for three different test objects being illuminated with white LEDs. In all four panels the chromaticity coordinates of the reference white LED are designated with the plus (+) symbol and the Planckian locus for reference. Top left : white background, radius = 0.0027. Top right: monotone stamp, radius = 0.0048. Lower left: multi-color stamp, radius = 0.0053. Bottom right: all three radii together with the chromaticity coordinates of the reference white LED.

Figure 11 shows the three-dimensional "tolerance zones" for the three test objects after the luminance dimension has been combined with the chromaticity radii for the three test objects. Only one luminance dimension was required because there was no significant difference between test objects in the luminance experiment. It is important to note, however, that there may be interaction between brightness and color that was not tested in this experiment**.**

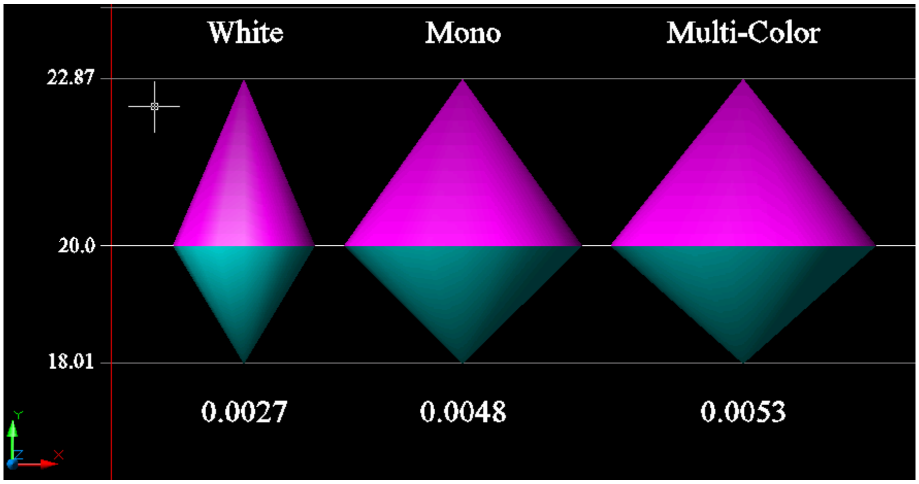

Figure 11: Three-dimensional tolerance zones. The radii vary according to the type of test object, but the luminance dimension is the same for all three test objects.

5.0 Discussion

This study supports and extends the work of Vasconez and colleagues [3,4], who also examined the impact of different colored illuminants on discriminability of colored and achromatic objects in a spatial, or side-by-side, comparison. In that experiment, subjects discriminated between the colors of achromatic and chromatic materials placed in simulated freezer cases. Target luminance was fixed at approximately 146 cd/m^2 and was not a variable in that experiment. The ability of subjects to discriminate differences between the illuminants was assessed.

Figure 12 shows the results of this study and those from Vasconez [3,4] for achromatic targets. Included in the figure is a four-step MacAdam ellipse used by the lighting industry to ensure consistent color of manufactured fluorescent lamps[5]. All three contours are roughly the same size indicating that different light sources and different methodologies yield very similar results when achromatic test objects are employed.

Figure 13 shows that the contours from Vasconez [3,4] and from the present study for colored objects are much larger than they are for achromatic objects. This suggests that, relative to the specification criteria for achromatic objects, some relaxation of the specification criteria for colored objects would probably be acceptable for users of white LEDs as illuminants.

Finally, it is important to point out that luminance is also an important specification criterion. Nominally identical white LEDs will vary in both chromaticity and luminance and, given that white LEDs are frequently used in spatially distributed clusters and arrays, these differences may be quite noticeable. The authors recommend that the "tolerance zone" for the white background (Figure 11) be used as a starting point for an interim standard for the sale and utilization of white LEDs with the understanding that this may be a conservative standard for many applications involving colored objects. Justification for this choice lies in the fact that the white background chromaticity tolerances are similar to those of the Vasconez [3,4]experiment and the traditional four step MacAdam ellipse tolerances. As far as luminance is concerned, however, the observed constancy in the tolerance zones for luminance for the different test objects suggests that adopting one luminance dimension tolerance would be equally applicable for both colored and achromatic applications.

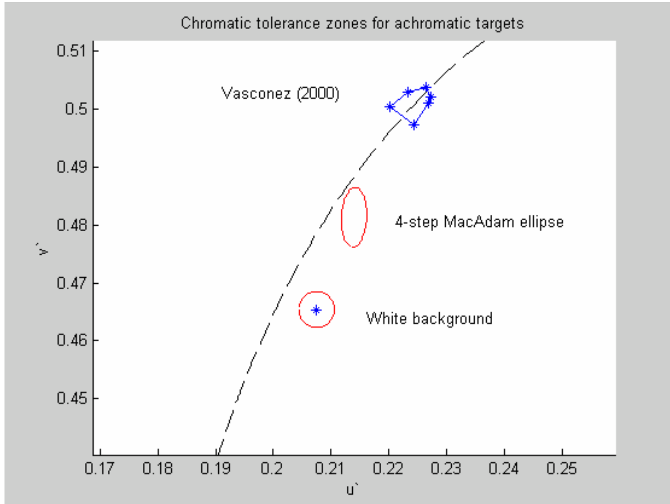

Figure 12: Chromatic discriminability for achromatic targets. The closed polygon shows results of the side-by-side comparisons from Vasconez (2000); the circle surrounding the plus (+) symbol represents the results of the present study's successive comparisons for the white background; the ellipse is a four-step MacAdam ellipse used by manufacturers for color consistency in the production of fluorescent lamps.

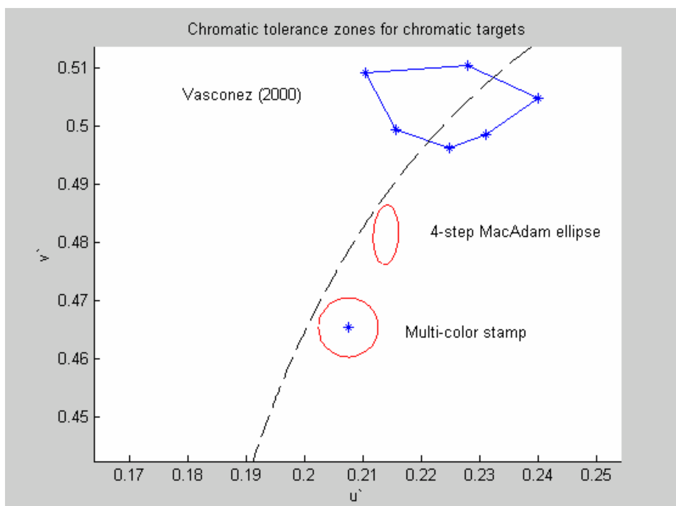

Figure 13. Chromatic discriminability for chromatic targets. The closed polygon shows results of the side-by-side comparisons from Vasconez (2000); the circle surrounding the plus (+) symbol represents the results of the present study's successive comparisons for the multi-color stamp; the ellipse is a four-step MacAdam ellipse used by manufacturers for color consistency in the production of fluorescent lamps.

6.0 Acknowledgments

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