EFFECT OF SMALL COLOR DIFFERENCES IN COLOR VISION ON THE MATCHING OF SOFT AND HARD PROOFS

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ABSTRACT: Are color matches between soft and hard proofs seen as a match by all color normal observers? This question arises because: (1) the color matches between soft and hard proofs are metameric, and (2) the color vision from one color-normal observer to another is not the same. This question was addressed theoretically and the results confirmed by color matching experiments. Matches made by one color-normal observer are acceptable to other such observers. However, they are not acceptable to people with slight color vision deficiencies (anomalous trichromats). Likewise, matches made by anomalous trichromats are not acceptable to color normals. The D & H Color Rule is a simple way to identify anomalous trichromats.

Soft Proofing

In the graphic arts, color monitors or "soft-color" displays provide the most rapid and cost effective way of previewing color pictures. Images on color monitors are called "soft" proofs because they disappear when the monitor is turned off. Soft proofs, despite their ephemeral nature, are increasingly used with scanners and color electronic pre-press systems (CEPS) to preview the color quality of the picture before films are exposed and before the very costly printing step. If the quality of a picture is unacceptable, the scanner or CEPS unit can be readjusted until the soft proof is acceptable. Although pictures on a

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color monitor may not, at this stage of development, exactly match press prints or hard proofs they nevertheless are very useful.

Soft vs. Hard Color Matches are Metameric

Because they are so very useful, efforts are underway to understand the characteristics of color monitors in order to improve the appearance match between soft and hard proofs. It is important to realize that no matter how closely the two types of images match, the match must of necessity be metameric. This is because soft displays utilize self-luminous red, green and blue phosphors while hard proofs use light-absorbing cyan, magenta, yellow and black colorants.

For example, a bright red color in a graphic arts print is made by overprinting magenta and yellow inks; this same color on a monitor is generated by exciting mainly the red phosphor. Figure 1 shows how very different the spectral energies are for such a matching pair of red colors.

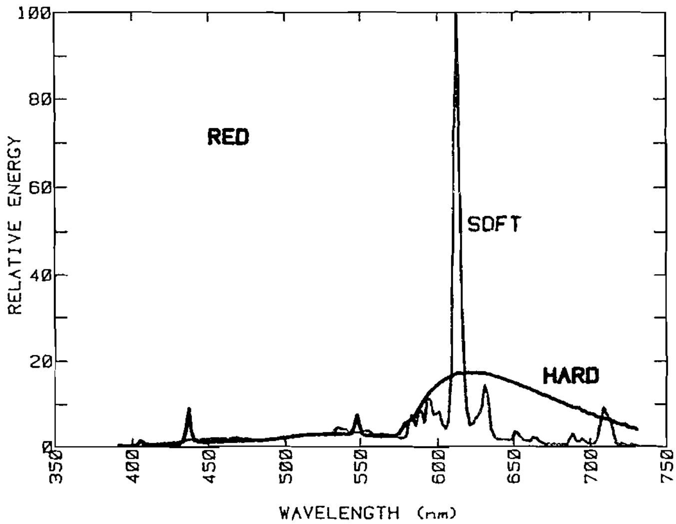

Figure 1. Spectral energies reaching an observer from a matching pair of soft and hard red colors.

The spectral energies reaching the observer from this pair of colors are so different that the match is clearly metameric; the monitor emits energy mainly at 612 nanometers while the energy reaching the eye from a color print encompasses a broad wavelength band.

Since the metameric condition between soft and hard colors arises because of the way the two systems generate colors it is of interest to compare the primaries typically used in each of these systems.

Figure 2 shows the spectral energy curves of a typical set of red, green and blue phosphors found in color monitors.

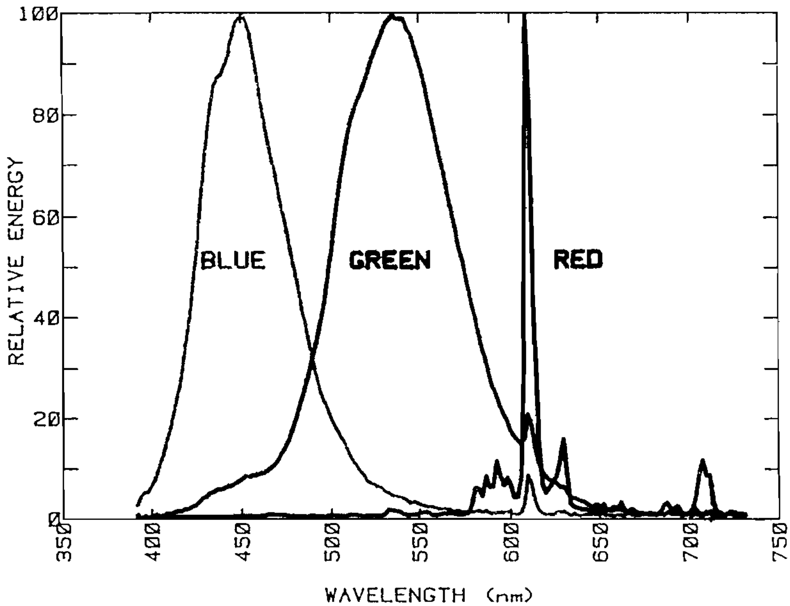

Figure 2. Spectral energy curves of a set of red, green and blue phosphors typically found in color monitors.

And shown in Figure 3 are plots of the spectral energies reaching an observer from the cyan, magenta, yellow and black colorants generally utilized in proofing and in printing.

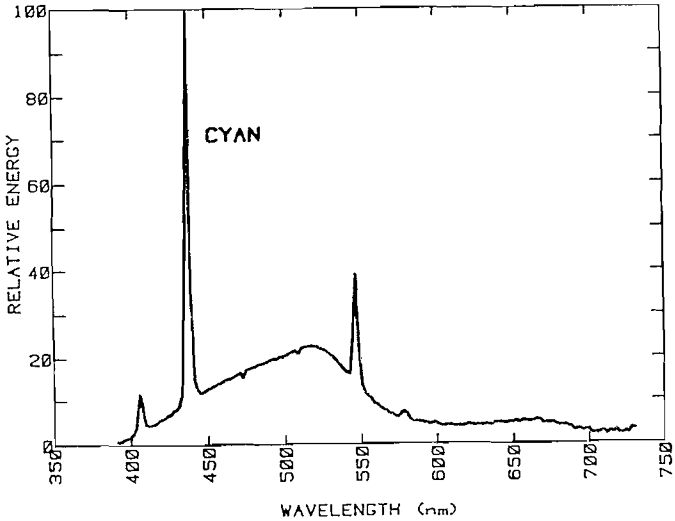

Figure 3a. Relative spectral energies reaching the eye from a solid cyan patch displayed in a viewing booth.

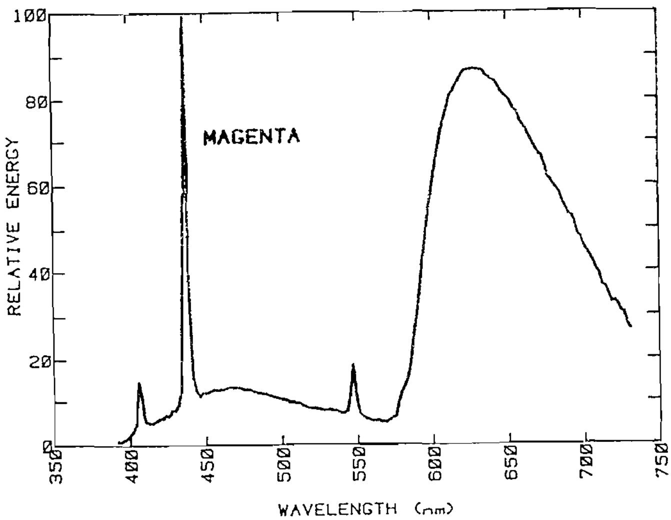

Figure 3b. Relative spectral energies reaching the eye from a solid magenta patch displayed in a viewing booth.

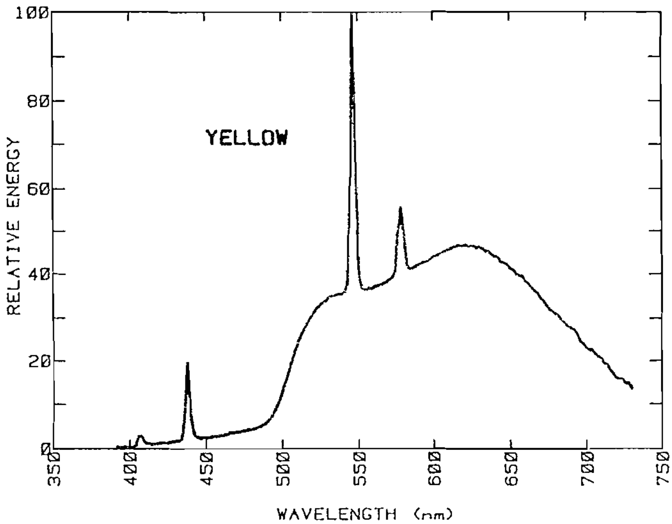

Figure 3c. Relative spectral energies reaching the eye from a solid yellow patch displayed in a viewing booth.

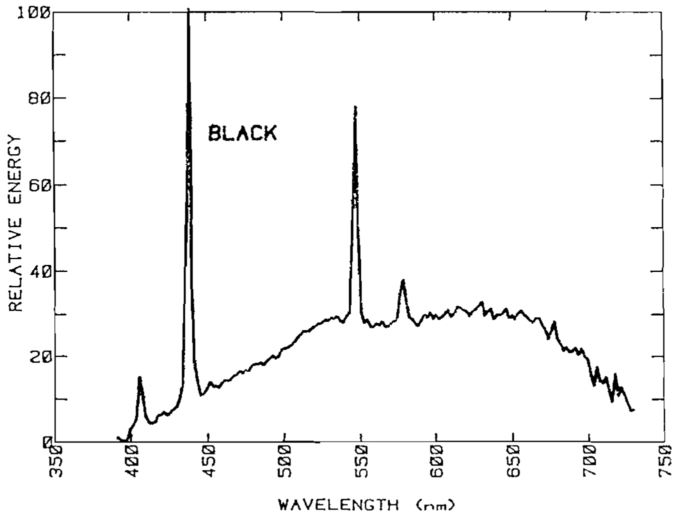

Figure 3d. Relative spectral energies reaching the eye from a solid black patch displayed in a viewing booth

The energy spikes in these curves are the mercury lines of the 5000 Kelvins fluorescent lights illuminating the colorants.

Is Soft Proofing Fundamentally Flawed?

Upon examining the curves in Figures 1 through 3, a color scientist might suspect that the strongly metameric nature of the matches produced by soft proofing could be its Achilles Heel; that is, it might be a fundamental flaw which could lead to the downfall of soft proofing as a reliable predictor of the appearance of a press print. This is because the appearance of strongly metameric colors can shift markedly from one observer to another due to differences in color vision even among normal observers. For example, one could imagine a printer who sees a soft and hard proof as matching but to the client they look significantly different. If shifts in color appearance are very large, soft proofing could conceivably be abandoned as a practical alternative to hard proofing. The purpose of this study is to see how serious this problem really is.

Objective

Given a pair of soft and hard colors which match to a reference observer, do they match to other observers, and if not, how large a color difference is seen between them? The objective of this study is to measure the size of this color difference.

Procedure

Two approaches were used to quantify the effect of observer variability when viewing soft and hard proofs:

(1) computation, using the published color-matching data for Stiles' twenty color-normal observers, and

(2) color vision experiments, in which observers adjust the color on a monitor until it matches a hard color. Four observers with normal color vision and two anomalous trichromatic observers

were used.

Both anomalous trichromats and normal trichromats use all three types of retinal cones in color vision. Where they differ is in the amount of either red, green or blue light needed for a match. Anomalous trichromats require more of one these primaries to obtain a match as compared with normal observers.

An overview of each of these approaches will now be given. The mathematical details appear in the Appendix.

I. Computation with Stiles' Twenty Observers

The first step of this approach is to generate, mathematically, the spectral curves of soft and hard colors which are seen to match by a reference observer, that is, which share the same set of tristimulus values to one observer.

The next step is, in effect, to "present" this metameric pair of colors to a group of twenty observers with differing but known spectral sensitivities. In essence these different observers are being asked whether they agree with the reference observer and see this metameric pair as matching or do they see them as different? If they do not look alike, the color difference between them can be expressed in CIELAB delta E* units. Since the color vision of these twenty observers is not identical, there can be as many as twenty individual answers to this question for each metameric pair of colors. 625 different pairs of metameric colors were studied. Figure 4 shows a plot of how many times a given delta E* was computed.

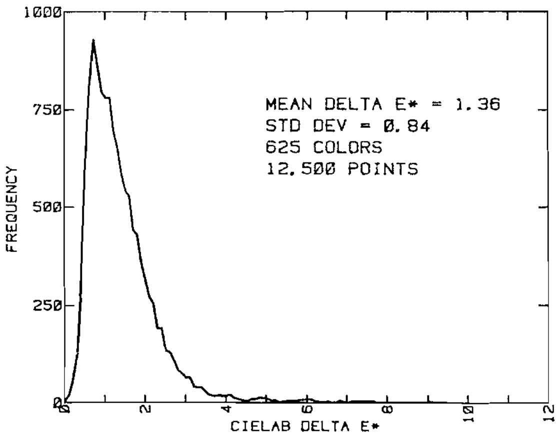

Figure 4. Number of times a given color difference (in delta E* units) was found.

The data of figure 4 indicate that Stiles' twenty observers agree very closely with one another. A match seen by the reference observer will be seen by the individual observers as different by at most 3.0 delta E* units, at 95 percent confidence limits. This value is surprisingly small. Dr. Roy Berns of the Munsell Color Science Laboratory at RIT was consulted to see if he could provide insights into these unexpected results. It turned out that he had made similar calculations with Stiles' twenty observers using paint metamers and likewise found the average observer difference between metameric pairs to be very low, a delta E* of less than one. His results are as yet unpublished.

Edwin Breneman also was asked to comment on these results. He suggested that the reason matching pairs of soft and hard colors are considered to be such strong metamers is primarily due to the very large differences in the red region of their spectral curves. In this region, hard colors have a broad reflectance band compared with the extremely narrow band of emittance found in soft colors. Breneman also points out that if a large part of the variation in Stiles' twenty observers is due to differences in the degree of yellowing of the eye lens from one observer to another, then one might expect to see only small differences between observers when they compare soft and hard colors. This is because variation in yellow filtering has little or no affect on the transmittance of red energy. In other words he is suggesting that there may be very small sensitivity differences in the red region between observers and this might account for the very small shifts in color appearance between soft and hard colors.

Paul Swift wondered if Stiles' twenty observers are truly representative of the range of color vision of graphic arts workers who are involved in making color judgments. In effect he is questioning whether the range of color vision of Stiles' group had been intentionally reduced by eliminating some observers. It is known from Stiles and Burch's 1958 report that their initial study involved 54 observers. Clearly there must have been a de-selection process to decrease the number of observers to the twenty that were published. Stiles and Wyszecki (1963) state that these twenty observers were selected because of their greater reliability and experience in trichromatic matching, without reference to their actual results. Still the uncertainty remains as to whether the range of observers is representative.

II. Color Vision Experiments

Because of this uncertainty and because of the surprisingly low average delta E* it was decided to supplement the above solely computational approach with a small number of actual color vision experiments.

Observer Selection

However before the soft-vs-hard color matching experiments could be done a small number of observers had to be chosen. The initial criteria for selection were: (1) two of the observers should represent the widest difference in color vision that we could find spanning the range of normal trichromats, and (2) each observer should be repeatable.

Prospective observers were screened using the D & H Color Rule (Biersdorf, 1977). This device allows one to discriminate between people having normal color vision and those with mild color deficiencies, that is, anomalous trichromats. Normal trichromats whose vision differs because of yellowing of the eye lens are also said to be differentiated with this Color Rule (Kaiser and Hemmindinger, 1980).

The D & H Color Rule is a slide rule device 36.7 x 7.8 cm, with two painted movable slides of constant lightness. One slide gradually changes color from purple to green through a neutral gray. It is labelled on the back with letters A to U. The other slide changes color from blue to brown through neutral gray. It is labelled with numbers 1 to 21 on the back. A portion of both colored slides appears through a rectangular aperture on the front of the rule, and the slides are adjusted until the closest color match is found. The match is metameric. The rule is then turned over and the number and letter identifying the match can be read. Not only is the color match strongly dependent upon the state of the observer's color vision but it also heavily depends upon the color quality of the illumination used in viewing.

Since the purpose here was to differentiate between the color vision of different observers, matches were made under the same light source, a Macbeth 5000 Kelvins viewing booth. Some twenty people were asked to make three matches each with the Color Rule. The average of the three matches for each observer are plotted in Figure 5.

The color matching results for most of the observers plot as an elliptical swarm with the major axis of the ellipse at about 45 degrees. The observers represented by this plot were considered normal trichromats and four of these were chosen: N, I, M and Z. Based on this D & H plot, observers N and Z were considered to represent the limits of the normal observer group. Observer N and Z are also the youngest and oldest in the group, respectively, with almost 45 years age difference between them.

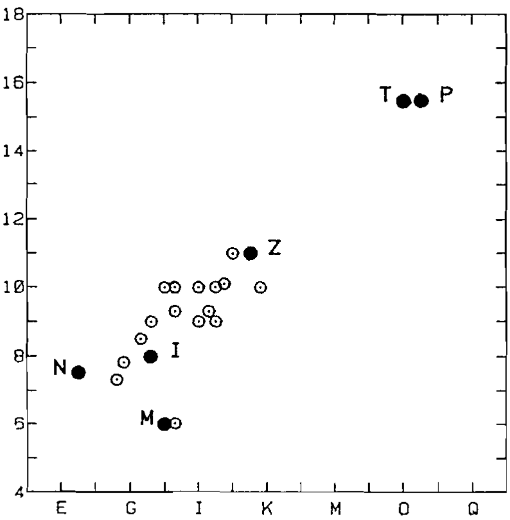

Figure 5. Observer matches plotted on D & H Color Rule graph.

Two of the observer results (P and T) plotted close to one another but at a considerable distance from the other observers. These two observers were considered to be anomalous trichromats. Normal trichromats found the D & H settings made by these two observers an unacceptable match and vice-a-versa. Finding two mildly anomalous trichromats provided the unexpected opportunity of doing the color vision experiments with a larger range of observers. It was decided to include these observers along with the four normal trichromats.

The two anomalous trichromats also took the Farnsworth-Munsell 100-Hue Test but it failed to reveal any color vision deficiency in one of the observers and only a slight one in the other. Compared with the Farnsworth-Munsell 100-Hue Test, the D & H Color Rule appears better able to discriminate between people with normal vision and those who are anomalous trichromats. This agrees with the conclusion reached by Biersdorf (1977).

Color Vision Experiments

Color Matching of Adjacent Color Patches

In these experiments the observer was asked to change the hue, chroma and lightness of a uniform color patch on a monitor until it matched a hard color. The light coming from the soft and hard colors was redirected by mirrors so that the pair of colors could be seen side-by-side separated only by a 3-mm vertical black line. Extraneous light was prevented from reaching the viewer by an opaque enclosure so that the observer saw only the soft and hard colors coming from the mirrors through a rectangular opening in the enclosure. The two color areas are both about 1-inch square and subtend an angle of 2 degrees at the observer. This aperture was surrounded by white paper to enable the viewer to adapt to a 5000 Kelvins reference white while doing the experiment. The illumination on the white surround was adjusted by dimming the 5000 Kelvins fluorescent ceiling lights until the white surround was slightly lighter than the patches being viewed. Five different hard color patches were used: red, green, blue, a medium gray made with cyan, magenta and yellow, and another medium gray made with black only. The two gray patches are designated CMY-Gray and K-Gray, respectively. These patches were produced with the 3-M Matchprint proofing process and are each 15 x 15 cm.

The patches were put, one at a time, into a GTI Graphic Lite SOFT-VIEW D50 Transparency/Print Viewer made by Graphic Technology Inc. This device was used because its illumination level can be dimmed so that a white in the booth has approximately the same luminance as a white on a color monitor. By comparison, the illumination level in conventional viewing booths is considerably higher.

The observer was asked to change the color on a Tektronix 4115B digital color monitor by depressing the appropriate keys on a keyboard linked to the monitor. Hue, chroma and lightness can be changed independently of one another, in increments of 0.25 or 2.0 CIELAB units at the option of the observer.

When an observer is satisfied with the match, the numerical specifications are recorded. The color patch is then replaced with another and this procedure is repeated until each patch has been matched twice. If repeatability is poor the observer is asked to make more than two replicate determinations.

The above procedure was followed for all six observers.

In general, normal observers found the matches made by the other normal observers to be acceptable. On the other hand, matches made by anomalous viewers were clearly unacceptable to normal observers. Similarly, anomalous observers definitely could not accept the matches made by the normal observers.

Color Matching of Separated Color Patches

In the above experiments observers were asked to vary the color of a patch until it matched another patch immediately adjacent to it. Side by side color comparison was used because it is easier for observers to make color judgments under these conditions and therefore smaller color differences can be resolved. However this viewing condition is not representative of the application of interest, namely, the color comparison of corresponding areas of pictorial images. Of necessity such areas are separated from one another and surrounded by various other colors which tend to confuse the judgment. It might be argued that there is far more latitude as to what is considered a match when comparing soft and hard color proofs than when adjacent color patches are compared against a uniform surround. The match between corresponding colors in a pair of images could be off but an observer might not be able to tell. Measuring the latitude of color matching in pictorial images is a major project and outside the scope of this work. However, some insights into this problem might be gained by removing the mirror arrangement used in the previous experiments and repeating the experiments with the soft and hard colors separated, rather than adjacent to one another.

This is the description of such an experiment. The mirror arrangement was removed and an opaque enclosure placed around the color monitor and GTI viewing booth to minimize stray light. Two square apertures, four inches on a side, were cut into the enclosure, one for viewing a section of the color monitor, and the other, the hard color in the booth. The distance between the viewing apertures was 57 cm (22.5 inches). The observer could see the appropriate sections of the color monitor and viewing booth when sitting about 1.5 m (5 feet) from the opaque surround. The color patch subtended 3.5 degrees at the observers eye. All five Matchprint color patches and five of the six observers (three normal and 2 anomalous) used in the previous experiments were also used in these new experiments. Everything else was the same.

The results of this experiment were identical to those in the previous experiment in which the patches were viewed side by side.

Conclusions

Color vision differences between **normal observers** appear to pose no problem for the comparison of soft and hard proofs.

Matches between soft and hard colors made by **mildly anomalous observers** are not acceptable to normal observers and vice-a-versa. This was found to be true even when the two colors were separated by almost two feet. Separating the patches did not seem to decrease the observed differences. This is an unexpected result and needs independent confirmation. The color matching experiments involved uniform color patches within a neutral surround. It remains to be seen if there will be a problem with mildly anomalous observers when soft and hard **pictures** are compared. This is because corresponding areas of the two types of pictures are not only separated but are surrounded by other color areas which might make it more difficult to detect a difference.

The D & H Color Rule is a very sensitive, fast and low cost means of screening people for color deficiencies.

If the disagreement between color-normals and anomalous trichromats persists when pictures are involved it is recommended that workers be screened for color deficiencies using the D & H Color Rule. Screening is advisable because of the high incidence of anomalous trichromats among Caucasian males -- one out twelve (Hurvich, 1981).

Acknowledgements

Burt Saunders conceived the method for calculating the effect of variation of color vision on the stability of the color match between soft and hard proofs; Reggie Henderson and Tom Bushman programed the method. I also gratefully acknowledge the help of Chihwe (Jeffrey) Wang in carrying out the color matching experiments. All work for the RIT Research Corporation.

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Appendix

Description of Computational Method for Assessing the Effect of Variation in Color Vision on Soft Proofing

1. **Generate the spectral reflectance curve of a hard color** using the spectral Neugebauer equation with Yule-Nielsen modification (Viggiano, 1987), four-colorant case, given:

   (a) a set of cyan, magenta, yellow, and black dot areas,

   (b) spectral reflectance curves of the sixteen Neugebauer primaries (obtained from the four solid colorants, their two-, three- and four-colorant overprints and white paper).

2. **Calculate a set of tristimulus values of the hard color** using:

   (a) the above spectral reflectance curve,

   (b) the spectral data for 5000 Kelvins light source, and

   (c) the color-mixture functions of the <u>average</u> of Stiles' twenty observers.

3. **Calculate the r,g,b phosphor intensities of the soft color** which would match the hard color to the average of Stiles' twenty observers. The r,g,b intensities are obtained by pre-multiplying the set of tristimulus values of the hard color by the inverse of the matrix consisting of the tristimulus values of the three phosphors, arranged by column.

   A phosphor intensity greater than one or less than zero indicates that the hard color is outside the attainable gamut of monitor colors. When this happens a new set of c, m, y, k dot areas is chosen and the program starts again at step 1.

4. **Calculate the spectral energy curve of the soft**

color which would match the hard color to the average of Stiles' twenty observers. This curve is obtained by summing the spectral energy curves of the three phosphors each weighted by the corresponding phosphor intensity calculated in step 3.

5. **Transform both the "hard" and "soft" sets of tristimulus values into corresponding sets of CIELAB L*, a*, b* values.**

6. **Compute the Total Color Difference, delta E*, between the above two sets of CIELAB values for each of Stiles' observers.**

7. Accumulate in a frequency histogram, (Figure 4) the number of times a given delta E* is found.

8. Start with a new set of c, m, y, k dot areas at step 1.

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