Visually Closest Cross-Gamut Matches Between Surface Colors

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Abstract

When emulating single, uniformly colored surfaces the most common aim is for the emulation to look as similar to the original as is possible given the constraints of how it is generated. The work presented here reports results of a psychometric experiment in which observers made choices from among the colors on the surface of a reproduction gamut, given original colors outside it. The resulting choices were found to follow trends identified in previous studies on self-luminous displays whereby the visually most similar colors preserved about twice as much lightness and hue as chroma. Such a trade-off among color appearance attributes can therefore be applied irrespective of the media between which colors are to be mapped.

Introduction

Given a set of original colors and a chosen means of reproducing them, some original colors will almost invariably be irreproducible using the chosen means as they will be outside its color gamut. Colors of some plastics cannot be matched by printing onto paper; some printed colors made using special inks cannot be matched using printers having standard colorants, etc. In such cases, when a color match is impossible, there can be a number of desired reproduction properties that are sought. For images this is typically pleasantness of reproduction and reproductions of single, solid colors are often intended to look as similar to the original colors as possible. In this paper the focus will be on what to do to achieve such similarity between an out-of-gamut original and its reproduction when both are reflective surfaces.

The question of how to substitute an original unmatchable color with a different reproduction to achieve visual similarity has been investigated in several previous studies[1-3] and their general consensus is that not all of the original's color attributes (i.e. lightness, chroma and hue) are equally important. More specifically, maintaining an original's lightness and hue was found to be more important than maintaining its chroma. Given such existing results it might at first not be clear why there is a need for more work on this subject. However, when a closer look is taken at previous studies, it becomes apparent that all of them have been performed exclusively for matches between self-luminous and reflective media (i.e. display and print). Furthermore, the most direct of the existing work,[2] where observers were asked to adjust a color from a given gamut to make it as close as possible to an out-of-gamut original, was performed entirely on a display.

The question asked here is, whether findings obtained using displays transfer to cross-gamut differences between reflective surfaces. The reason for wanting to obtain such data is that there are color-critical applications in which the color of one surface needs to be represented by emulating it on another. For example, when emulating the colors of fabrics in print or attempting to represent a spot color, printed with special inks, using the colorants of a digital printer, even small departures from an optimal solution can be perceptible and even unacceptable. As a key aspect of this work is applicability to the reproduction of individual colors and as perceptibility and acceptability thresholds for these are relatively low, it is important to understand how visual closeness is judged specifically for reflective color reproduction media.

It is also worth noting why there has been no psychometric work on cross-gamut surface to surface matching to date and the reason is the increased difficulty of trying to let an observer make adjustments to their choice of surface color properties as compared with doing so on a self-luminous display. A solution to this challenge will be presented after a brief examination of the meaning of color difference versus similarity and finally results will be reported for the experimental procedure followed in this study.

Distance *versus* similarity

The units of ideal color difference equations represent just noticeable differences (JNDs). Pairs of colors judged as only just distinguishable are therefore described by a color difference (ΔE) of one. Then the meaning of a ΔE of two units between a pair of colors is that there exists a third color on the line connecting them in an ideal, perceptually-uniform color space that has $\Delta E=1$ from both colors of the pair. In general a ΔE of n means that there are $n-1$ intermediate, one JND-spaced colors along the line between the color pair whose difference it is.

Therefore, given a color there are spheres in an ideal, uniform color space that have it as their centre and whose every point has the same color difference from the central color and this color difference is the sphere's radius. For representations in non-ideal color spaces (which applies to all current ones) the ideal sphere is replaced by another geometric figure that furthermore varies with location in the space. The key point here is that for every given color there is a multitude of other colors that are equally different from it.

Let us then ask the question: "For a color c and the set D of all other colors that are a given distance from it, what will be the result of asking observers to pick the most similar member of D compared to c?" If similarity is the same as distance then for a sufficiently large sample the result will be a uniform distribution of choices across the entire set D. If, however, color appearance attributes have different levels of importance then observers' choices will concentrate in specific parts of D. A consequence of such differences in importance are then also the results of previous work on cross-gamut visual similarity where colors that favor one dimension over another are chosen instead of colors having the smallest overall difference.

Having an accurate color difference metric is therefore not the end of the story and simply apply it when having to choose how to reproduce an out-of-gamut color on a given color reproduction medium will not result in the most similar looking choice. Instead it is necessary to understand the relative importance given to the three color appearance attributes when an observer is asked to judge similarity.

Experimental setup and method

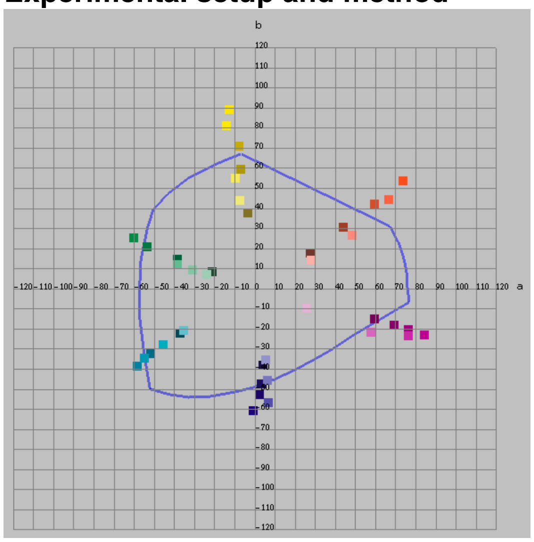
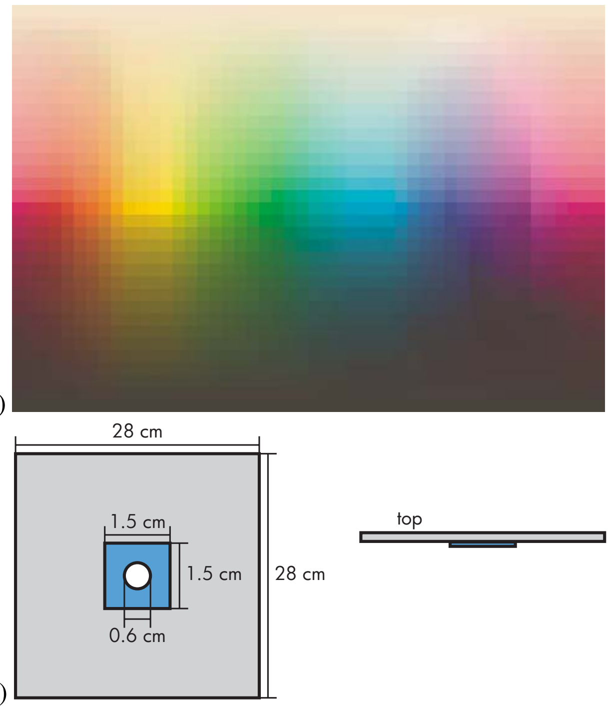


Figure 1: Original colors (squares) and reproduction gamut (line) in CIECAM02 ab (2° observer, D50, 2000 lux, average surround condition, 20% background reflectance).

Forty two color chips printed on an offset lithographic press using custom inks were chosen as the set of original surfaces that were to be emulated using prints made with a HP Designjet 5500ps on a HP Heavy Weigh Coated substrate (Fig. 1). The original colors were chosen so that sets of seven of them were of virtually the same hue and formed transitions from light, medium chroma via a high chroma and then to a dark, medium chroma. All prints were viewed under ISO 3664 P2 viewing conditions[4] (i.e. D50, 2000 lux, 20% reflectance background) and the choosing of the visually closest reproduction for each original color was performed by 15 observers taken from a pool of 14 females and 16 males (i.e. choices for each original color's reproductions were made by a different set of 15 observers).

The aim of the experiment was to get each of the observers to choose that printed reproduction, which looked most similar to the given original color. The mechanism used to allow for this relied on two components: First, a print of a sampling of colors from the reproduction medium's gamut surface where each color patch had a size of 8.4x8.4 mm (Fig. 2a). Note that the sampling was chosen so as to place the cusp (i.e. most chromatic color) at each hue at the same vertical location in the print as this facilitated choices for the observers based on a pilot experiment. Furthermore, separate prints of the gamut surface were made for each of the set of original colors of similar hue that covered a ±20° hue interval around them, which allowed for greater resolution in the gamut surface's sampling. Second, taking each of the original color chips (15x15 mm), cutting a 6 mm diameter aperture in it and mounting it behind an opening in a piece of 28x28 cm gray cardboard (with an angular subtense in excess of 10° - Fig. 2b). Note that the cardboard had a spectral reflectance like that of the background against which the gamut surface print was viewed. The reason for mounting the color chips behind an opening in the cardboard was to avoid issues of successive color contrast and to stabilize the observers' state of adaptation.

(a)



(b)

Figure 2: (a) Sampling of the entire reproduction medium gamut's surface, (b) mounted original color chip (note that only the relationship of the color chip to the aperture in it is to scale – the chip is relatively much smaller when compared to the board).

With each observer the following procedure was then followed:

1. The observer was asked to sit down at a gray table and instructed as follows: "You will be shown prints containing a large number of color patches and given a gray board containing a color chip in its centre. The chip will have a hole in its middle. Please, position the hole in the color chip on top of the printed color patches to make the color showing through the hole be as close to the color of the chip as possible."

2. For each original color chip, selected in a random order, the following procedure was followed:

   a. The print of the gamut surface for the hue interval around the color chip's hue was placed in front of the observer.

b. The board with the mounted original color chip was given to the observer.

c. The observer then proceeded to place the board on top of the gamut surface print and, looking at the color they saw through the aperture moved the board around until the color from the gamut surface print seen through the aperture in the original color chip was the one they chose.

d. Once the observer decided the final location of the chip's aperture, a transparent overlay was placed on top of the mounted chip in register with the gamut surface print and the chip's aperture's position was marked. The overlay was then removed.

e. After the observer completed a set of choices, the locations on the gamut surface print - recorded on transparent overlays - were measured in terms of spectral reflectance.

As can be seen, the key to getting observer choices for surface to surface visual closeness was the method for letting them view the reproduction gamut's surface through an aperture in the original color and registering their choices on a transparent overlay.

Results

The above experiment resulted in 42 sets of 15 color pairs and the first step in their analysis was to look at the degree of inter-observer variation. The 15 reproductions chosen by the observers for each original had their medians computed in CIECAM02 *Jab*,[5] which represent the visually–closest in–gamut color as judged by the whole group (the *group choice*).

To express inter-observer variation, the Euclidean distances in CIECAM02 *Jab* (ΔE_{Jab}) between individual observer choices and the group choice were computed. The means and maxima of these means for each of the 42 originals as well as differences in lightness (ΔJ), chroma (ΔC) and metric hue (ΔH) are shown in Figure 3. As can be seen, individual observers agreed well with the overall group choice, with smaller differences between the lightnesses of individual choices than between their chromas (with hue variation in-between the two). It was furthermore found that variation was not correlated with the magnitude of color difference between original and reproduction – in other words that agreement for originals closer to the reproduction gamut was similar to that for originals further away from it. This, somewhat surprising result is encouraging as it means that, if observer choices are successfully predicted using a model, then these predictions will be equally representative for large and small color differences.

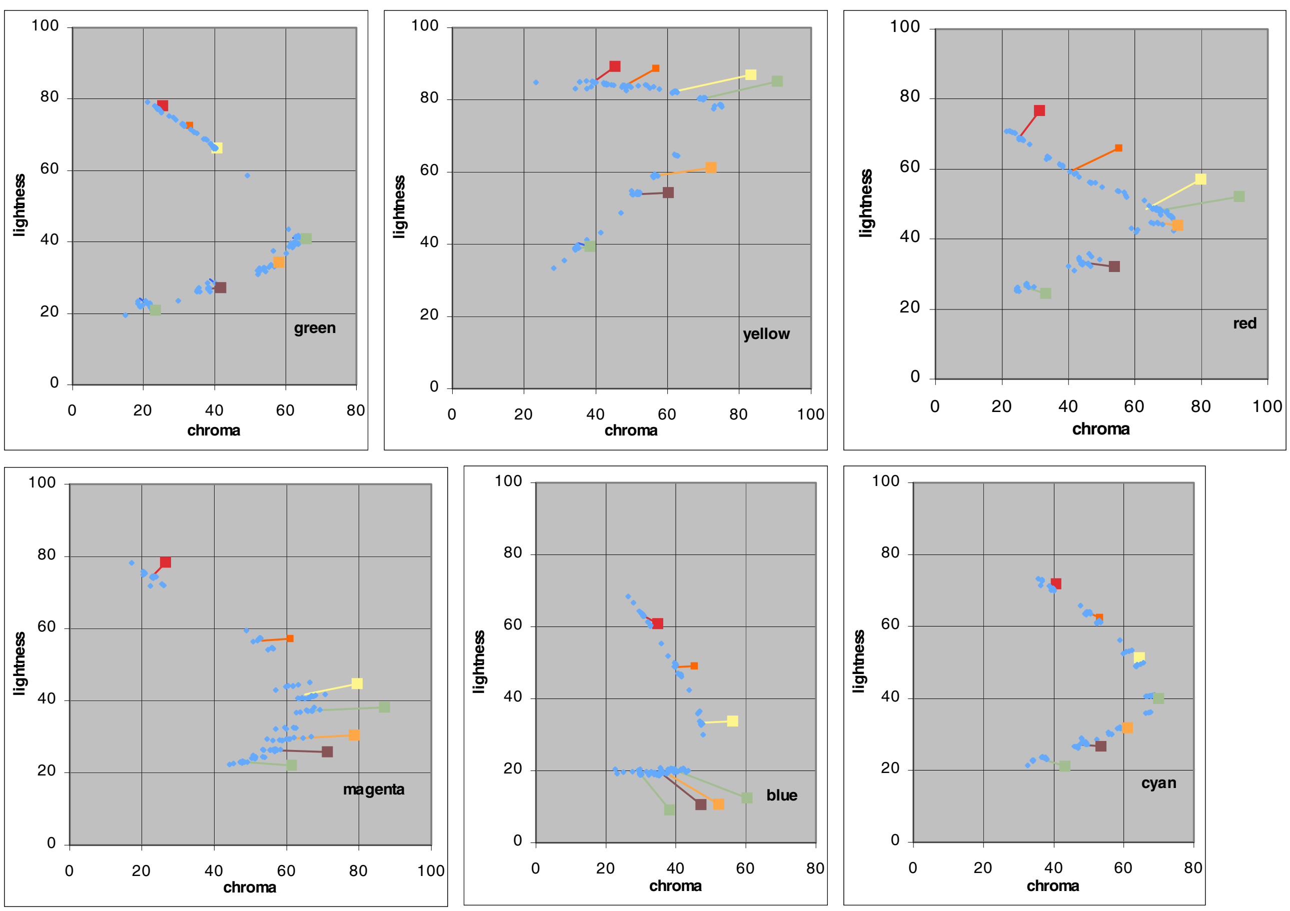


Figure 4: Properties of group choices: squares – original colors, colored lines – pointing to group choices, blue diamonds – individual choices.

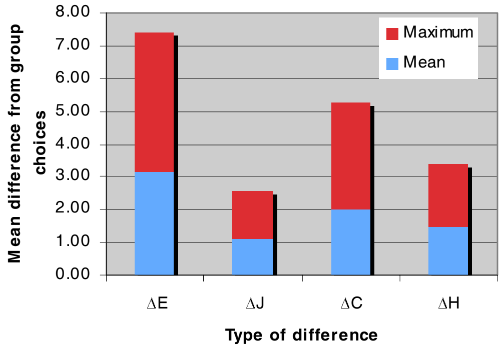


Figure 3: Overall inter-observer differences.

Taking the 42 originals and corresponding group choices and visualizing them in CIECAM02 (Figure 4) shows that the simulations chosen by these observers are not towards the gamut boundary colors with smallest distance. Instead, lightness and hue are given significantly more importance than chroma with a median ratio of $\Delta J:\Delta C:\Delta H=[1 : 2.68 : 0.84]$. What can also be seen is a significant level of variation in how chroma is weighted with respect to lightness and hue for the individual colors (Figure 5).

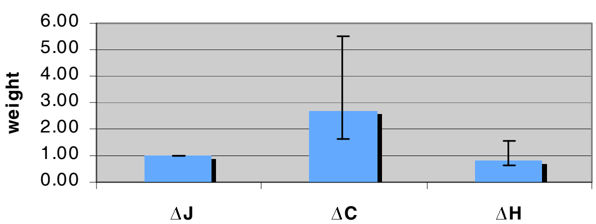


Figure 5: Median ΔJ:ΔC:ΔH ratio and 50% of ratio range.

In addition to the visually closest choices made by this group of observers, a further, less rigorous, experiment was conducted with graphic arts professionals who make a living by manually adjusting color emulations. The reason for doing this was to see how the choices of a naïve group of observers relate to those made by skilled professionals. Two companies (one in the US and the other in the UK) were therefore paid to emulate the same set of original colors on a pair of digital printing systems each. The resulting lightness, chroma and hue trade-offs they made are shown in Figure 6.

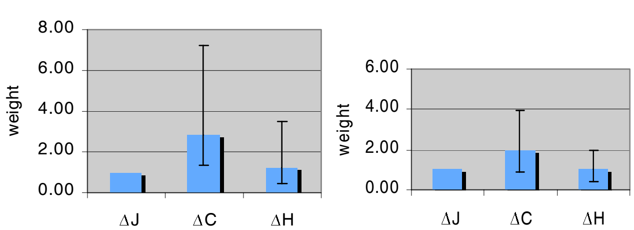


Figure 6: Median ΔJ:ΔC:ΔH ratio and 50% of ratio range for professional color matching in (left) US and (right) UK.

The greater degree of variation seen here can be attributed to the fact that these emulations are the work of two individuals as opposed to the central tendency of a group. In terms of the median ratios, it can be seen though that the same trends as found before still hold: chroma is sacrificed most and lightness and hue are considered of greater importance.

Predicting observer choices

Given the data sets described above, an optimization technique was used to compute a set of [kJ,kC,kH] weights that minimizes the differenced between the reproduction gamut surface colors with minimum weighted color differences[1] computed using it ($\Delta E_{wt}=((\Delta J/kJ)^2+(\Delta C/kC)^2+(\Delta H/kH)^2)^{1/2}$) and the choices made by the naïve group as well as the choices made by professionals. Figure 7 then compares the ability of straight minimum color difference in CIELAB and CIECAM02 and weighted color difference in CIECAM02 with optimized weights to predict the visually closest choices described before. As can be seen, the use of [kJ,kC,kH]=[1,2.6,1.3] significantly outperforms the other solutions and gives a good approximation of what a manual process would result in.

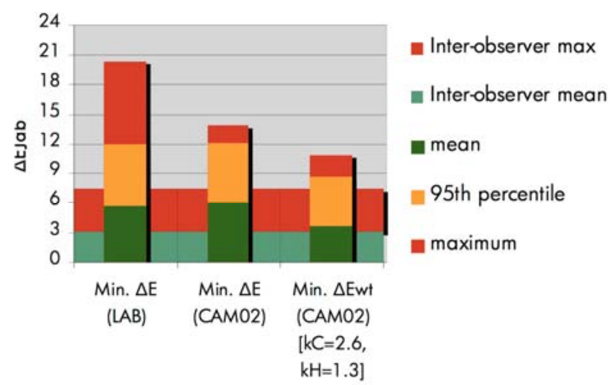


Figure 7: Predicting observer choices of visually closest colors.

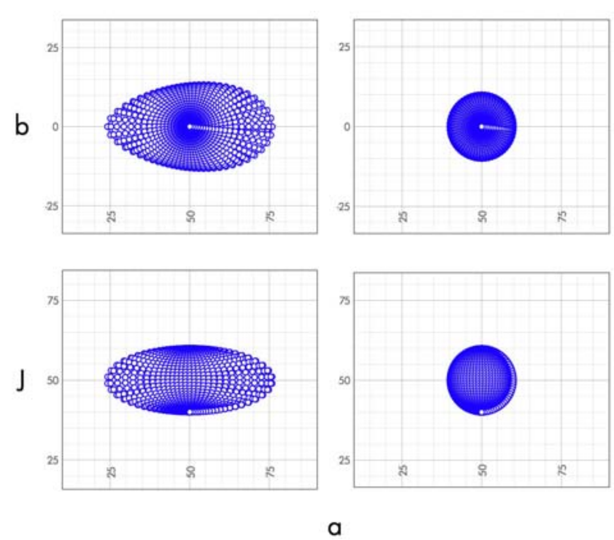


Figure 8: Set of points with no more than 10 units difference from Jab=[50, 50, 0] using (left) weighted and (right) non-weighted Euclidean distance metrics.

To illustrate the effect of using weighted color difference equations, Figure 8 shows two sets of points projected onto the *ab* and *aJ* planes in CIECAM02. The set of point on the right has Euclidean distances from the Jab=[50,50,0] point of no more than 10 units whereas the set on the left has distances from that same point of no more than 10 units using the weighted distance with [kJ,kC,kH]=[1,2.6,1.3] values. Minimizing the weighted distance is therefore equivalent to taking the shape shown on the right and increasing its size until one of its surface points touches the gamut. In the Euclidean distance case the only difference is the nature of this shape, which becomes a sphere rather than being the distorted ellipsoid of the weighted equations.

Conclusions

Allowing observers to make choices about what surface color from a limited color gamut looks most like an out-of-gamut original resulted in data that is in very good agreement with previous studies performed either between displays and print (with limited observer control) or entirely on a display (with full observer control). As all previous studies and the work presented here agree on lightness and hue needing to be preserved approximately twice as much as chroma, using such weights when trying to find the closest color across gamut differences can be recommended irrespective of how those gamuts are obtained – be it by additive or subtractive means.

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Author Biography

Ján Morovič received his Ph.D. in color science from the Colour & Imaging Institute (CII) of the University of Derby (UK) in 1998, where the title of his thesis was To Develop a Universal Gamut Mapping Algorithm. After working as a lecturer in digital color reproduction at the CII he became senior color scientist at Hewlett-Packard in Barcelona, Spain. He is also the chairman of the CIE's Technical Committee 8–03 on Gamut Mapping.