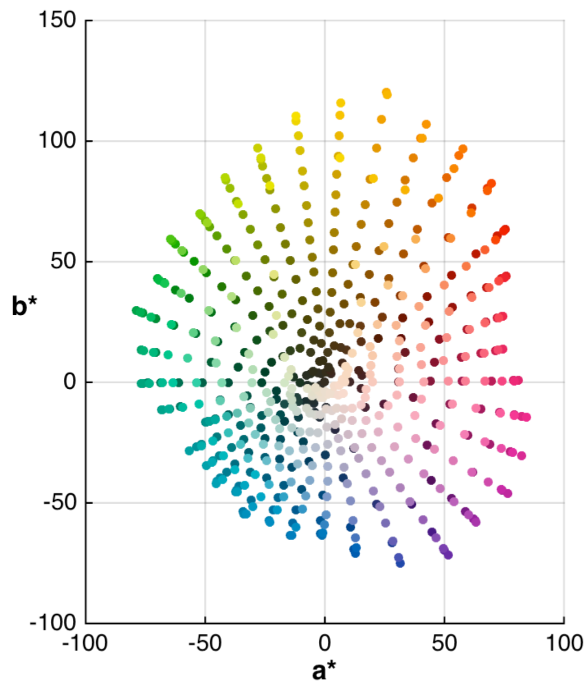
Report to

LIBRARY OF CONGRESS

Creation of Color Analysis Target
Task A: Define the spectral coordinates for the reflective human vision environment



Submitted by:
David R. Wyble, Ph. D.
President, Avian Rochester, LLC
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Avian Rochester, LLC
PO Box 1210, Webster NY 14580
(585)259-5956 • www.avianrochester.com

Executive Summary

In support of the digitization efforts of the Library of Congress, a solicitation, *Creation of Color Analysis Target*, was issued and subsequently awarded to Avian Rochester, LLC for the design and fabrication of a Next Generation Target (NGT) for color camera calibration. The NGT will be designed to address the shortfalls in commercially available targets. For the purposes of this report, those shortfalls are limited color gamut, and a lack of durability for typical laboratory usage. The lack of durability has a direct impact on the accuracy of the calibrated values for the target. Any physical damage to the target surface requires calibration to reassert the color coordinates for each patch, meaning the cost of operations for a target is directly tied to its durability.

This report addresses the requirements of Task A of the project, *Define the spectral coordinates for the reflective human vision environment*. The goal of Task A is to proposed a set of colors for the NGT. Sets of existing colors were examined: some that are commercially available, and others that are historically significant. From these color sets, a distribution of colors is proposed for the NGT. These colors are intended to optimally fill the available color gamut given the durability requirements.

Subsequent tasks will identify colors more representative of cultural heritage materials, as well as specific substrate and pigment systems that will fulfill the other requirements of the NGT.

Introduction

The Library of Congress (LC) supports an ongoing effort to digitize materials. The requirements for high quality imaging include controlling the system for accurate color, meaning that imaging devices must be characterized for accurate color capture. One critical need identified by LC is for a robust color target to facilitate this color characterization. Towards this end, Avian Rochester, LLC responded to Solicitation Number: LCOSI15Q0058, *Creation of Color Analysis Target*, and was subsequently awarded the contract. This report is the first part of the fulfillment of that contract, specifically Task A: *Define the spectral coordinates for the reflective human vision environment*.

The particular requirements identified for the next generation target (NGT) are:

1. it will better fill the appropriate color space;
2. it will have increased durability, and be suitable for regular laboratory use;
3. it will be able to be lightly cleaned;
4. it will be compatible with existing software systems (LabviewDICE and OpenDICE).

This report addresses the first of these: filling the appropriate color space. Ideally, we might consider just making a target that covers all colors. However, it is impractical (and impossible) to attempt to fill the entire color space perceived by the human visual system. As a stand-in, we will use the Pointer Gamut[1] of colors as the target for distribution of colors in the NGT. It will be seen that this dataset will prove difficult to implement and still meet the other requirements in the above list. Indeed, as will be described below, the selection of samples that constitute the Pointer gamut present the current project with conflicting goals: robustness and durability vs large gamut.

The balance of this report will address these two considerations to fulfill requirement #1: first, what colors are available in current targets?; and second what colors might be selected for inclusion in the NGT? Given the importance of the Pointer Gamut for this project, we will first introduce that work, with an emphasis on the implications of applying that color set to the current project. With the Pointer Gamut as a metric, we will review the distribution of colors in a few modern targets commonly used for camera characterization. To those data sets, we will add the data from the Munsell Color Order System. Finally, we conclude with an estimate of the distribution of colors we can expect to implement in the NGT.

Review and Applicability of the Pointer Gamut

There are four sources of the data published for the Pointer Gamut: The Munsell Limit Color Cascade; the Matte Munsell Atlas[2]; the Royal Horticultural Society Colour Charts; and a mixed set of "coloured paper, paint samples, plastics, inks, and a large range of textiles."[1] All of the data were previously measured and tabulated except the final mixed category. In total there were 4089 colors, of which 1393 were measured specifically for the Pointer paper.

For this work it is important to understand how well should we expect to reproduce these colors. In particular the Munsell Limit Color Cascade consists of printed inks, which are able to provide greater chromas than the mixed paints anticipated to be used for the NGT. Printed inks will require the addition of a durable top coat, which raises the issue of consistent gloss. Another problem is the limited spectral shapes in printed inks. The durable glossy paints will be based upon a greater number of pigments and therefore present greater spectral variety. While the spectral nature of the NGT target will not be specifically addressed, it is generally accepted that greater spectral variety in a camera target will generally provide a better performing target.

Pointer makes many references to *optimal colors*, by which he means the maximal chroma colors proposed by Ostwald and published by Macadam.[3] These colors start as calculated spectra, where the only possible values are zero and unity, with at most two transitions in the visible range. Effectively this means each particular spectrum is either a band pass or band exclusion (notch), in each case the band (notch) is of a specific width to achieve the desired lightness. However, since these assume the physically unattainable reflectance of zero at some wavelengths, Pointer applied a 0.56% reflectance of Macadam's spectra to ensure the resulting colors could be reasonably compared to the other datasets. Depending on the hue, this term served to reduce the maximum chroma to a greater or lesser degree. Pointer plots the chroma limits of these colors (often referred to as *Macadam Limits*) for comparison, but they are not included in the Pointer Gamut colors. In a sense, the Macadam colors can be considered the theoretical limits against which the practical Pointer colors can be compared.

Notes on CIELAB[4] Coordinates and Plotting Techniques

Ultimately, the reference data for all of the targets discussed here are spectral reflectance factor. In basic terms the reflectance is the ratio of that light reflecting off a surface divided by that light incident on the surface. This measurement is performed at across all wavelengths in the visible spectrum, here 380nm to 730nm, sampled every 10nm, for a total of 36 data points per reflectance spectrum. Figure 1 shows the spectral reflectance factor of a few colors.

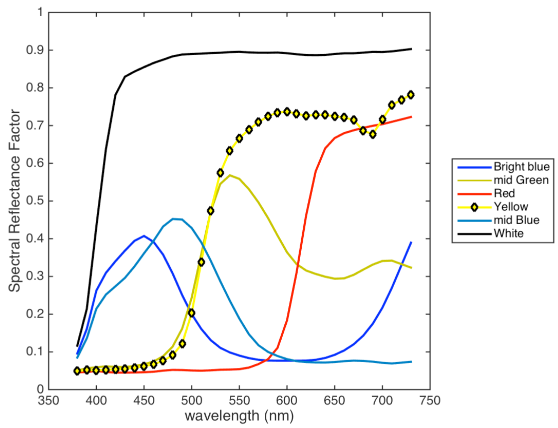


Figure 1. Example spectral reflectance curves.

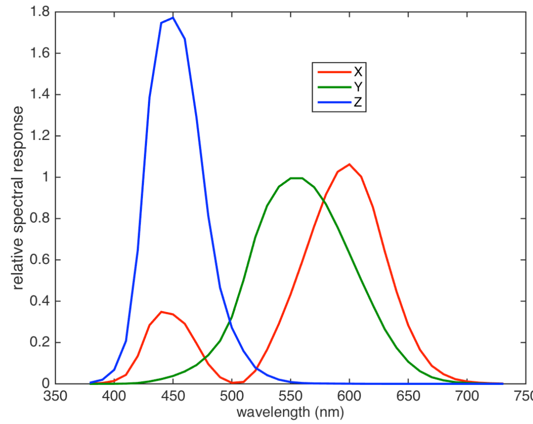


Figure 2. CIE[4] color matching functions (1931 2°).

While spectral reflectance factor is an important property of an object, it does not represent the *color* of that object. Object color also depends on the light under which the object is illuminated as well as the properties of the human visual system. Figure 2 shows the CIE weighting curves[4] for color matching functions that are designed to model human perception (also called the *standard observer functions*). After applying a light source to a reflectance curve, the resulting spectrum is weighted by the three color matching functions. These spectra are summed, to produce CIEXYZ coordinates. These coordinates are accepted as representative of the signals sent to the brain by the retinal neurons, but still require further transformation to model perceived color. The final transformation yields colors in the CIELAB space, with coordinate axes L^*, a^*, and b^*.

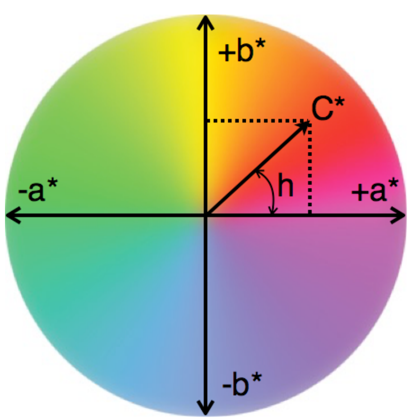


Figure 3. CIELAB space, projected onto the a* b* plane. The origin represents all achromatic colors. C* (chroma) represents the distance of a color from the achromatic point,

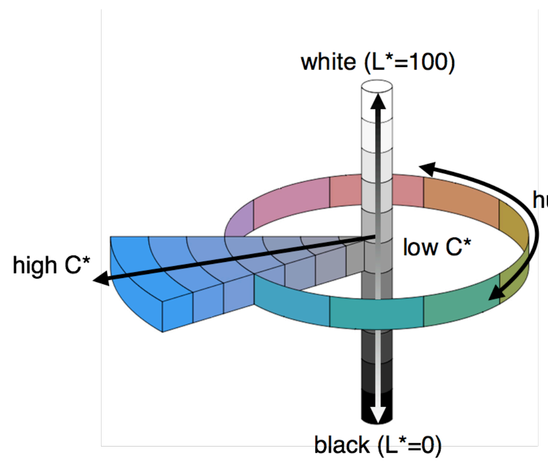


Figure 4. Isometric view of CIELAB space.

Figures 3 and 4 show CIELAB color space in two projections. Descriptively, L^* represents whiteness and blackness, with a range of 0 (black) to 100 (white). a^* represents redness (positive a^*) and greenness (negative a^*). Similarly, b^* represents yellowness (positive b^*) and blueness (negative b^*). So L^* holds the achromatic information, while a^* and b^* hold the chromatic information. C^* quantifies how chromatic a color is, but is distinct from the hue angle (h). Note that C^* and h hold same information as a* and b*. The former is in cylindrical coordinates, the latter Cartesian.

CIELAB represents a great improvement over any color spaces available before 1976. The most important feature is its applicability for color difference. That is, a distance between two CIELAB colors correlates reasonably well with the perceived color difference between those two colors. This has wide ranging applications in commerce and research, in particular for establishing tolerances for industrial processes. Here, we will use this uniform distance to optimize the distribution of NGT patch colors across color space.

All Pointer CIELAB data were originally calculated using illuminant C and the CIE 1931 2° standard observer. They are transformed (using established chromatic adaptation methods) to D50/2° for all plots and analyses here. Figure 5 shows *b** vs *a** (left) and *L** vs *C** (right) projections. Colors are approximate renderings, and only for illustrative purposes. These notes on color transformation and plot colors apply to the Munsell coordinates plotted below as well, which were originally calculated using illuminant C and the 1931 2° standard observer.

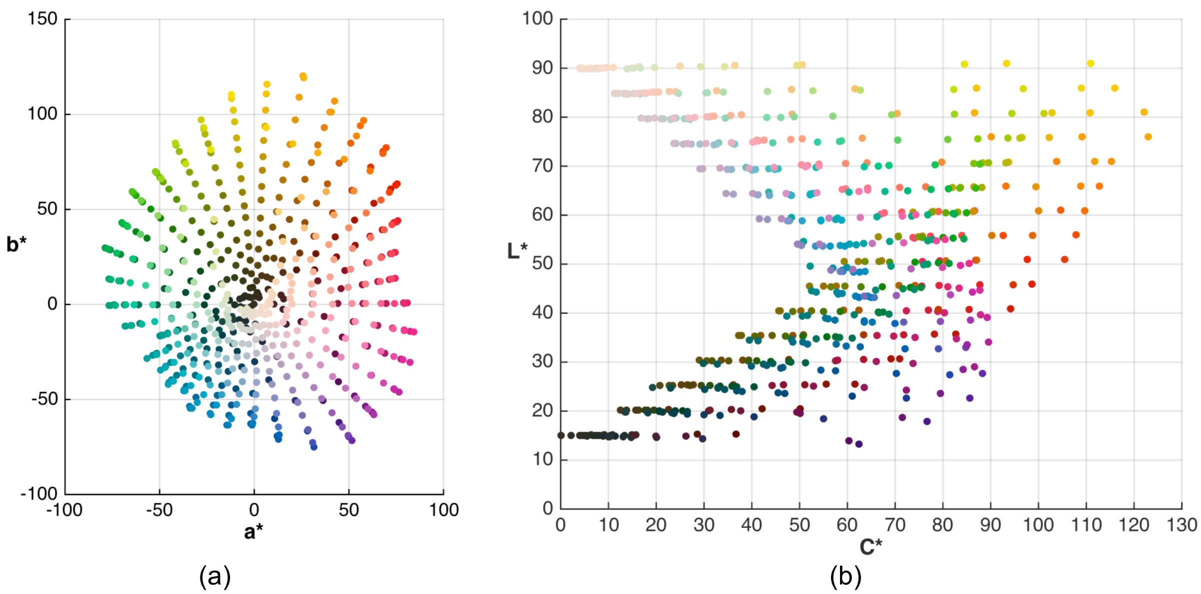


Figure 5. Distribution of Pointer Gamut colors when transformed to D50/2° CIELAB. For this and all similar plots below, (a) shows the projection onto the a*-b* plane, (b) shows L* vs C*.

As implied above, the Pointer Gamut extends beyond the chroma that can be reasonably expected in a target that otherwise has the required properties of the NGT. In particular, durability and uniform gloss. For the purposes of this report, the Pointer Gamut represents the maximum gamut of colors that can be possibly implemented in a physical target without the constraints of the NGT.

Within the baseline color set established by the Pointer Gamut, the distribution of colors in existing commercial color targets will be explored, along with other available physical color samples.

Current Color Targets

There are almost as many commercially available color targets as there are industries interested in color. This work will focus on two targets that historically been important and popular in color photography and digital imaging: ColorChecker Classic ("Classic"), and the ColorChecker Digital SG ("SG"). This product line was originally developed by Macbeth, later produced by GretagMacbeth, which ultimately merged with X-Rite. Both targets are pictured in Figure 6.

These targets have been acquired by Avian Rochester, and the data below represent measurements of these specific physical targets. Measurements were made using Konica Minolta FD-7 bidirectional spectrophotometer, as are all subsequent measurements discussed in this report, unless specifically noted otherwise. Likewise, gloss measurements reported here are made using a BYK-Gardner micro-TRI-gloss. The BYK simultaneously measures 20°, 60°, and 85° gloss. Both instruments have been recently factory serviced, and are NIST traceable through their respective factory certifications.

(a) (b)

Figure 6. Color Checker targets: ColorChecker Classic (a) and ColorChecker SG (b). Images from xrite.com.

Color Checker Classic

The Color Checker Classic has been very popular among color photographers for decades. It is approximately the size of a US letter page, and contains 24 patches, each about 40mm square. It was specifically developed to include patches with the spectral reflectance similar to foliage, skin tones, and other naturally occurring materials. It also includes cyan, magenta, yellow, red, green, and blue patches which are representative of the primaries of color printing and photography. Finally, there are six spectrally flat neutral patches.

There are several features of the Classic that are also desirable in the NGT, and some that should be avoided:

- *Patch size*. For characterization or calibration of a digital camera, patch images are typically averaged to reduce noise. For all anticipated applications, the Classic patches are large enough for averaging.
- *Surface fragility*. The Classic patches are matte Munsell papers, meaning that any physical contact beyond the lightest of brushing will mar the surface permanently.
- *Gloss uniformity*. Calibrating a color digital camera requires samples of as uniform gloss as possible. Table I summarizes the gloss measurements of the Classic target. The JND metric was proposed[5] for 60° gloss, but for the present study was also applied to the other gloss angles. For all three gloss angles, the JND is significantly lower than the standard deviation of the measurements. Therefore the spread of the data should be perceptible to an average observer. Note importantly that this does not address how sufficient this gloss uniformity is when applied to the digital imaging application; verifying the impact of gloss uniformity on the camera calibration is outside of the scope of this report.

Table I. Gloss data for ColorChecker Classic

Metric	20° gloss	60° gloss	85° gloss
mean	0.48	2.05	3.39
std dev	0.34	0.80	0.98
min	0.02	0.67	1.83
max	1.48	3.60	5.41
JND*	0.07	0.28	0.45

* The JND is strictly valid only for 60° gloss.[5]

- *Color uniformity*. Color uniformity is important since the digital data for at least some portion of the patch will be averaged. For this test, four of the patches were measured 20 times in random locations with the FD-7 spectrophotometer. The spectra were converted to D50/2° CIELAB coordinates. From the mean CIELAB coordinates of each patch, the Mean Color Difference from the Mean (MCDM) was calculated. MCDM is an indication of the perceptual spread of the patch measurements. As with the gloss JND metric, it is not clear precisely how MCDM translates to digital imaging performance, but it should represent a reasonable stand-in for minimum expected within-patch camera variation. Table II summarized these measurements.

Table II. Color uniformity data for ColorChecker Classic

Sample	$\overline{L^*}$	$\overline{a^*}$	$\overline{b^*}$	MCDM (ΔE^*_{ab})
magenta	52.05	50.94	-14.32	0.16
red	42.86	52.04	28.81	0.10
green	55.60	-38.90	32.14	0.40
white	95.59	-1.20	2.58	0.15
white calibration tile	92.76	-0.23	2.50	0.014

Notes on color measurements:

1. The magenta, red, and green are all from the third row of patches, which in its entirety is blue, green, red, yellow, magenta, and cyan.
2. The final row of the table, "white calibration tile," summarizes 20 measurements of the white FD-7 calibration tile, completed without moving the instrument or tile. This MCDM can be used as the instrument repeatability, indicating the portion of the other MCDMs that can reasonably be attributed to the inherent performance of the instrument.

Color Checker SG

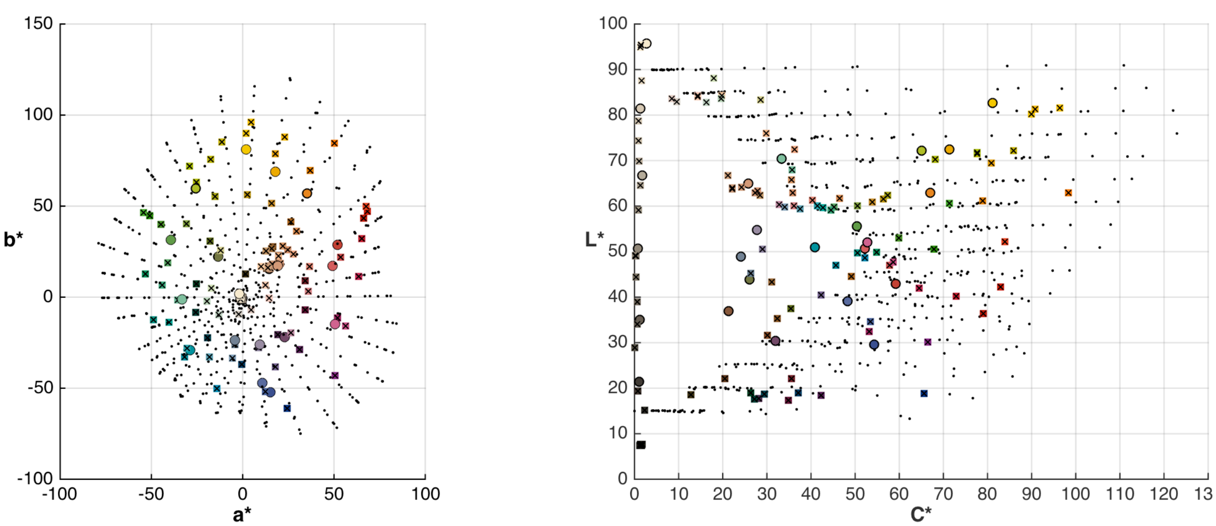
The Color Checker SG represents an improvement to some shortfalls of the Classic. It is the same form factor: about one US letter sheet. It contains 140 glossy patches, each being 12.5mm square, of which 59 are neutrals and 81 are chromatic. The perimeter patches are alternating white, mid-gray, and black, totaling 44 of the 59 neutrals. These perimeter neutrals aid in the determination of the illumination uniformity, an important property to quantify in any scientific imaging system. The specific distribution of the chromatic patches will be discussed below. To aid with backward compatibility to the Classic, the SG has a 6x4 matrix of patches near the top center that are the same colors and layout as the Classic, albeit more glossy.

All of the properties listed for the Classic are important for the SG as well. The smaller patch size, while large enough for averaging of digital data, are too small for either gloss measurements or a statistical analysis of their uniformity. A visual inspection does show some obvious gloss variation; in particular the black patches appear the most glossy, with some of the chromatic patches appearing markedly less so.

Regarding surface fragility, the semi-gloss surface of the SG make it less susceptible to minor physical contact. However, the manufacturer's product notes specify: "Avoid all physical contact with the colored squares."

Distribution of Colors of Current Color Targets

Figure 7 shows the same projections as the Pointer Gamut above. Pointer Gamut colors are small black circles and the Color Checker Classic (circles) and Color Checker SG (X's) are colorized. The distribution of both targets is good, and both have an adequate emphasis on the neutral scale.



(a) (b)

Figure 7. Distribution of colors from ColorChecker Classic (colored circles) and ColorChecker SG (colored X's). Small black circles are Pointer Gamut, and the same distribution as shown in Figure 5.

The Munsell Color Order System

The Munsell Color Order System was devised in the early twentieth century by Albert Munsell, an artist and teacher who wanted to address the need for a numerical method of color communication. Until then colors could be communicated imprecisely with words ("sky blue") or by the physical transfer of a representative colored artifact. Munsell configured the system to align with perceptual axes: lightness (which Munsell called "value", or whiteness/blackness), chroma (color intensity) and hue (the color name). When we communicate verbally we typically name a hue ("yellow") and possibly a chroma or lightness modifier ("pale yellow" or "light yellow"). Using the Munsell system all of these can be precisely denoted in the 3D perceptual system along the value, chroma, and hue axes.

The original system was created by Munsell himself, mixing paints until he had constructed a series of colors that, when organized along their axes, each represented an equal perceptual difference from the next. That is, the color difference imposed when increasing the value by one unit is the same color difference perceived when decreasing the value by one unit. So the whole space was fashioned of physical paint samples, each with a specific notation. In the early 1940's it was noted that some of the colors did not seem to align so uniformly with respect to their neighbors, so a large visual experiment[6] was undertaken to address these nonuniformities. The resulting set of colors are available from many online sources[7] and are referred to as the Munsell Renotation Data.

Figure 8 shows the Munsell Color Order System displayed in the same fashion as the Pointer Gamut plots above. Note that for comparison the axes' limits are the same as the Pointer Gamut plots.

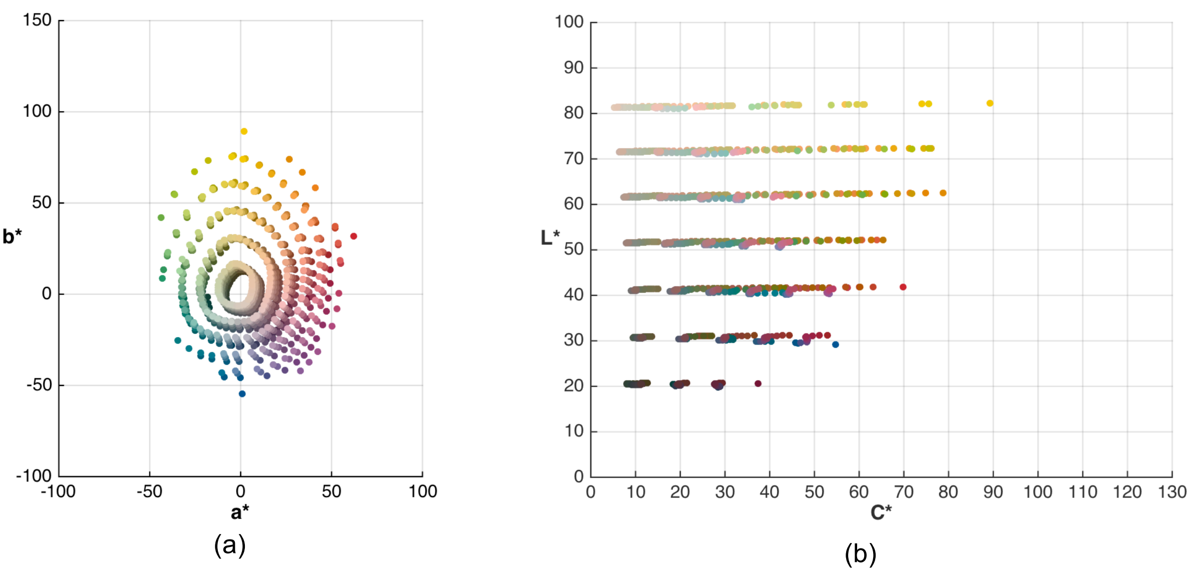


Figure 8. Distribution of Munsell Renotation colors colors when transformed to D50/2° CIELAB. Munsell color are deliberately configured to lie in planes of constant value (equivalent to L* after scaling), as seen by the horizontal linear groupings in the right plot.

For the purposes of this report, the benefit of the Munsell Renotation Data is its uniform perceptual arrangement. These data represent a gridded distribution of colors that uniformly fill the available space. All of the measurements will be in CIELAB, which is not as uniform as Munsell in all regions of color space. However the Munsell data, after conversion to CIELAB, will maintain perceptually uniform spacing and provide the basis for optimally distributing of the NGT patch colors.

Estimate of Next Generation Color Distribution

The limitations imposed by the requirements of the NGT imply that the Pointer Gamut is not practically achievable. In particular the uniform gloss and high durability eliminate many of the high-chroma colors in that Gamut. Therefore the best estimate of the gamut is the Munsell system, which is based upon glossy mixed paints. The patches leading to the Munsell Renotation Data were produced in the 1940's, so the measurements of a current Munsell Book of Color can provide better estimates of the colors available, particularly the high chroma colors. The plots below show measured data of the highest chroma color present on each of the 40 hues in a modern Munsell Book of Color (glossy edition). These new colors still do not extend as far as the Pointer Gamut, but they do markedly increase the gamut shown by historic Munsell colors.

The final consideration to the distribution is the set of colors in the existing ColorChecker targets. These measurements are the same as plotted above, but include the measurements of the modern Munsell Book of Color. These three data sets are shown, along with the Pointer Gamut for reference, in Figure 9.

The dispersion of colors in Figure 9 represents a reasonable expectation of the high-chroma colors (in essence the gamut limits) that can be achieved using the high-gloss, high-durability exterior paints. Further it is reasonable to assume that an appropriate distribution of colors can be formulated that fill this gamut in a visually-uniform fashion.

For actual estimates of the specific locations of colors, some assumptions must be made. First, the total number of colors in the target will be 120. There will be 20 neutral colors. Of the remaining 100 colors, 20 will be colors representative of cultural heritage materials (to be addressed in the Task B report). Therefore from the gamut range described, estimates of the coordinates of 80 colors will complete the balance of the NGT colors. The procedure for identifying the proposed locations was to first examine the planes of constant value for the Munsell data. The 80 chromatic patches were distributed among the seven values planes from 2 to 9, approximately corresponding to L* of 20 to 90. The planes of value 5, 6, and 7 represent the largest numbers of colors, so more colors were allocated to those regions. For each value plane, the selected number of colors were distributed uniformly among the Munsell and both ColorChecker colors. Proposed colors are plotted in Figure 10 (the small black points representing the Munsell and ColorChecker colors for reference).

Regarding the set of proposed colors, it is important to note that these are targets only. The needs of the NGT are to fill the available color space as completely as possible while retaining the other requirements discussed in the introduction. The practical impact of this is that the actual colors in the final product should be similarly distributed as shown in these plots, but will not likely have precisely the same coordinates as shown here. Specific color coordinates will be determined in Tasks 3 and 4 (selecting the base material and the color pigment system).

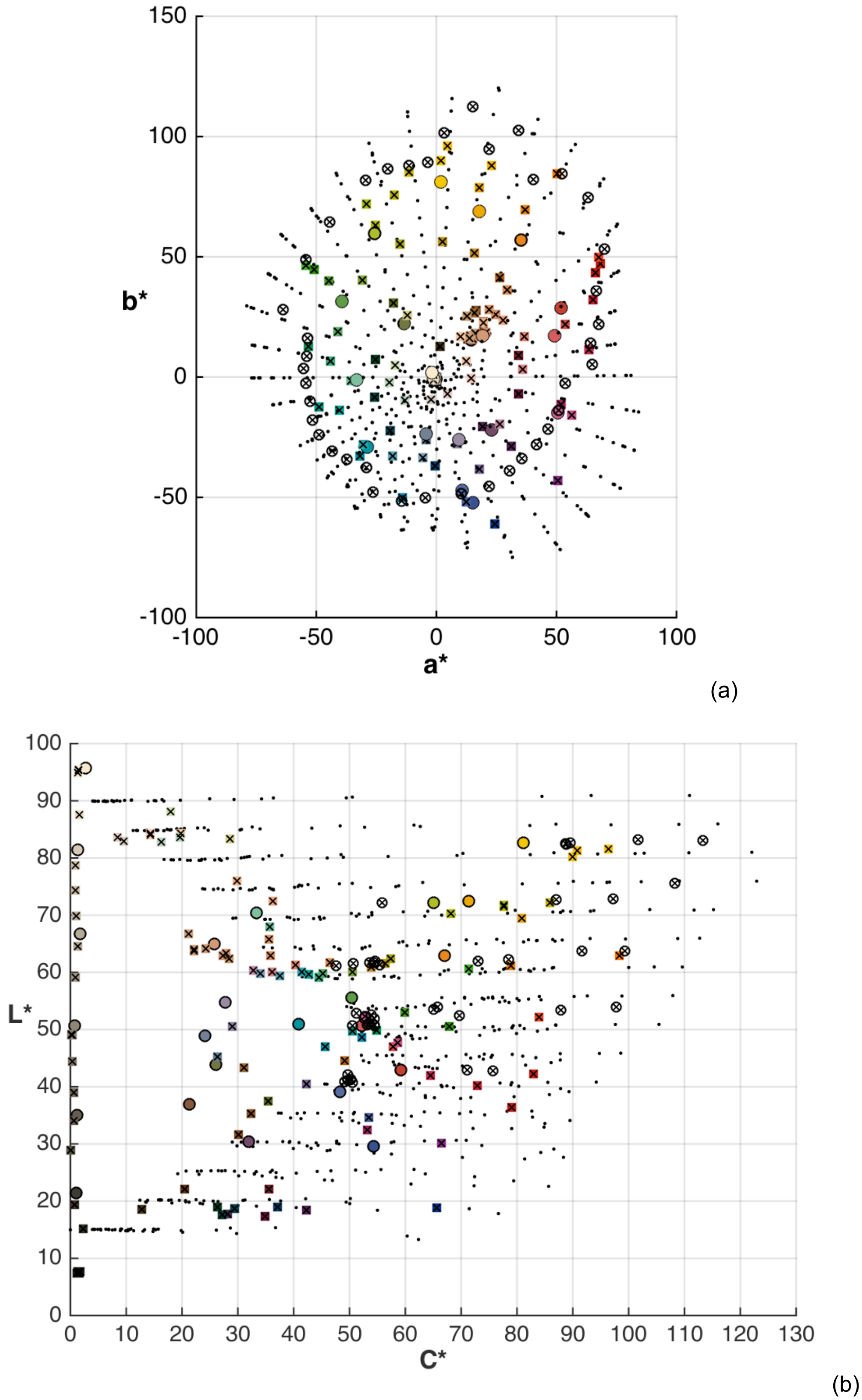


Figure 9. Distribution of measurements from the high-chroma colors (⊗) of a modern Munsell Book of Color, Glossy edition. These modern colors extend further into color space than the renotation data, created from paint mixtures in the 1940's. Also shown are ColorChecker Classic (●) and SG (☒). Pointer Gamut is shown for reference (•).

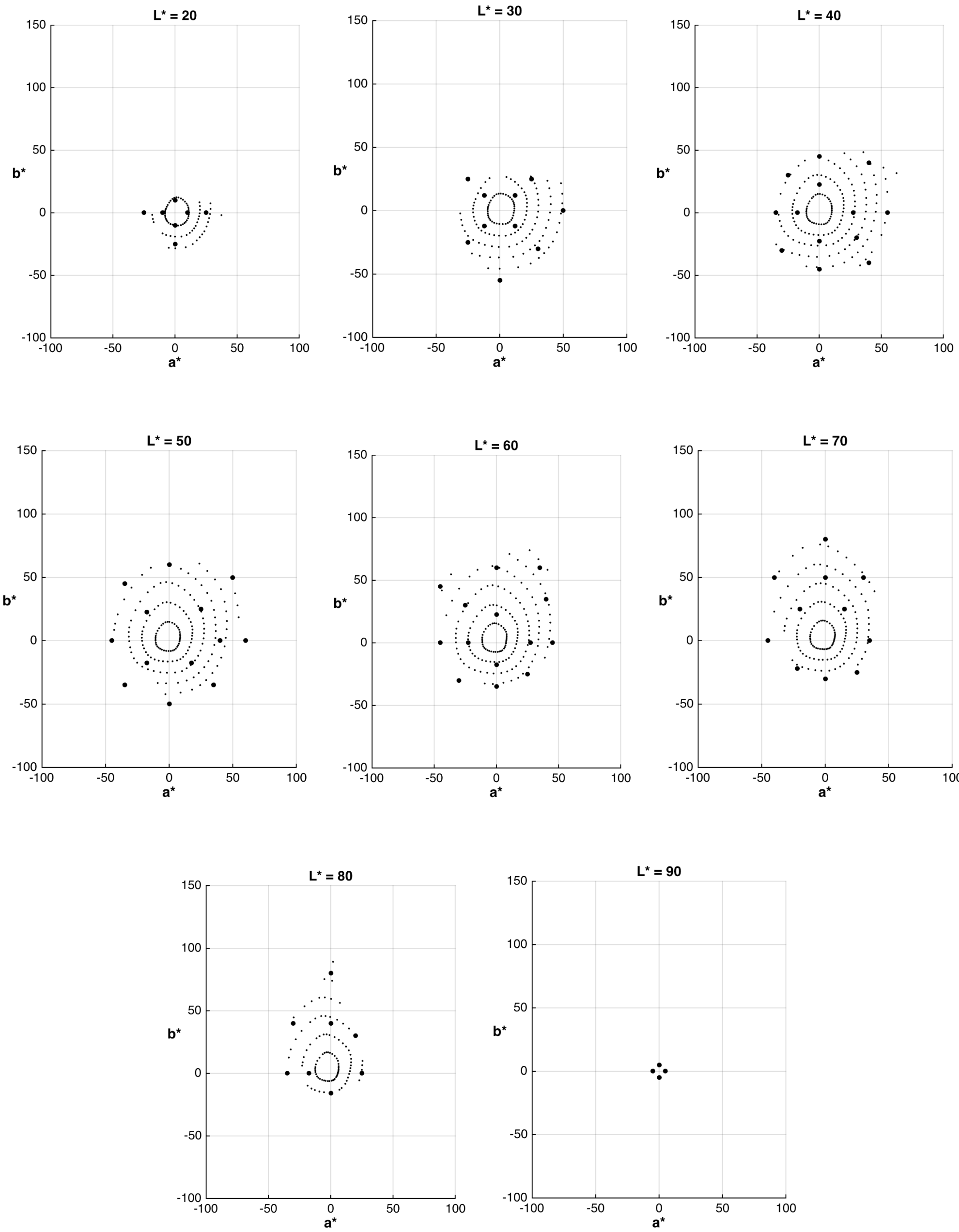


Figure 10. Location of proposed NGT colors (large circles), shown in as a*-b* projections in each lightness plane. Munsell and ColorChecker colors (small circles) are shown for reference. There were no colors in the datasets with L* of 90 or greater, but those shown are estimates of what might be available with the paint system. Note importantly that neutrals and cultural heritage colors are not shown in these plots. These colors are enumerated in the appendix.

Conclusion and Future Work

In support of the digitization needs of the Library of Congress, a project has been initiated to design and produce a new target for color camera characterization. The requirements for this Next Generation Target (NGT) are to better meet the needs of the library imaging community: better represent cultural heritage materials in terms of color; better general coverage of the range of available colors; and a more durable target for laboratory use. An analysis has been completed including several sources of potential colors for the NGT. Considerations on the final proposed distribution of these colors were based on the requirements of the NGT, primarily the physical durability, and color and gloss uniformity. The target basis for the distribution was the Munsell Book of Color, Glossy Edition. This book provides a set of colors that can be reasonably expected to attain the properties and gamut needed for the NGT.

Missing from the proposed distribution are those colors more representative of cultural heritage materials. This will be addressed in the next phase: *Task 2: Define the coordinates for cultural heritage materials by logical category*. Once the complete set of proposed colors are identified, the means for production will be evaluated, specifically the selection of substrate and its impact on gloss, and the selection of a color pigment system, and its impact on the final gamut of the NGT.

References

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2. Color Science: Concepts and Methods, Quantitative Data and Formulae, 2nd Ed. G. Wyszecki and W.S. Stiles, John Wiley and Sons, New York, 1982.
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5. Standardization of Perceptual based Gloss and Gloss Uniformity for Printing Systems, Ye.Ng, *et al*, Proc. SPIE 5294, *Image Quality and System Performance*, **26** (2003).
6. Newhall SM, Nickerson D, Judd DB. Final report of the O.S.A. subcommittee on spacing of the Munsell colors. *Journal of the Optical Society of America*, **33** (1943).
7. For example: `www.rit.edu/cos/colorscience/rc_munsell_renotation.php`, retrieved October 29, 2015.

Appendix Table A1: Enumeration of proposed colors for NGT

L*	a*	b*	L*	a*	b*
20	25	0	50	-45	0
20	0	-25	50	0	-50
20	-25	0	50	60	0
20	0	10	60	45	0
20	0	-10	60	0	60
20	10	0	60	-45	0
20	-10	0	60	0	-35
30	25	25	60	27.5	0
30	-25	-25	60	0	22.5
30	30	-30	60	-22.5	0
30	-25	25	60	0	-17.5
30	12	12	60	35	60
30	-12	-12	60	25	-25
30	12	-12	60	-30	-30
30	-12	12	60	-45	45
30	0	-55	60	-25	30
30	50	0	60	40	35
40	55	0	70	30	50
40	0	45	70	25	-25
40	-35	0	70	-22	-22
40	0	-45	70	-40	50
40	27.5	0	70	15	25
40	0	22.5	70	-20	25
40	-17.5	0	70	0	80
40	0	-22.5	70	-45	0
40	40	40	70	0	-30
40	40	-40	70	35	0
40	-25	30	70	0	50
40	-30	-30	80	0	-16
40	30	-20	80	0	80
50	40	0	80	-35	0
50	50	50	80	25	0
50	35	-35	80	-30	40
50	-35	-35	80	0	40
50	-35	45	80	-17.5	0
50	25	25	80	20	30
50	17.5	-17.5	90	5	0
50	-17.5	-17.5	90	0	5
50	-17.5	22.5	90	0	-5
50	0	60	90	-5	0