Evaluation of Color Mapping Algorithms in Different Color Spaces

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ABSTRACT

The color gamut supported by current commercial displays is only a subset of the full spectrum of colors visible by the human eye. In High-Definition (HD) television technology, the scope of the supported colors covers 35.9% of the full visible gamut. For comparison, Ultra High-Definition (UHD) television, which is currently being deployed on the market, extends this range to 75.8%. However, when reproducing content with a wider color gamut than that of a television, typically UHD content on HD television, some original color information may lie outside the reproduction capabilities of the television. Efficient gamut mapping techniques are required in order to fit the colors of any source content into the gamut of a given display. The goal of gamut mapping is to minimize the distortion, in terms of perceptual quality, when converting videos from one color gamut to another. It is assumed that the efficiency of gamut mapping depends on the color space in which it is computed. In this article, we evaluate 14 gamut mapping techniques, 12 combinations of two projection method across six color spaces as well as R'G'B' Clipping and wrong gamut interpretation. Objective results, using the CIEDE2000 metric, show that the R'G'B' Clipping is slightly outperformed by only one combination of color space and projection method. However, analysis of images shows that R'G'B' Clipping can result in loss of contrast in highly saturated images, greatly impairing the quality of the mapped image.

Keywords: Gamut Mapping, Wide Color Gamut, Video Processing, Color Processing

1. INTRODUCTION

The introduction of Ultra-High Definition (UHD) television in the commercial market is imminent and with it corresponding UHD content. However, for several years, commercial displays compliant with both High Definition (HD) and UHD television systems will have to coexist. During this transition period, both HD and UHD content will also be broadcasted.

The UHD standard format differs from HD in many ways. The first difference is that UHD requires at least 10 bits per color channel (30 bits per pixel) while HD uses only 8 bits (24 bits per pixel). Furthermore, the achievable color gamuts (the scope of possible color values) are different, UHD being able to represent much more colors. Indeed, UHD television relies on the ITU-R Recommendation BT.2020[1], which covers 75.8% of the CIE 1931 xyY color space[2] whereas HD television relies on the ITU-R Recommendation BT.709[3] and covers only 35.9% of this color space (see Figure 1).

Thus, when reproducing UHD content on HD televisions, some color information may lie outside the reproduction capabilities of the television. To ensure that the colors displayed by the television, are as close as possible to the original ones, colors have to be mapped to the display's (usually limited) capabilities. This operation is usually referred to as gamut mapping. Conversion of HD content for accurate reproduction on UHD displays is straightforward (and will most likely be integrated in all UHD commercial displays), since UHD has higher color reproduction capabilities than HD. However, adapting UHD content to HD displays entails much more problems since loss of color information is inevitable. The arrows illustrated in Figure 1 provide some examples of such loss of color information due to gamut mapping.

Identifying an efficient gamut mapping algorithm is of prime importance for broadcasters since they need to integrate such a technology in their UHD pipeline. Gamut mapping consists of projecting color code values of a

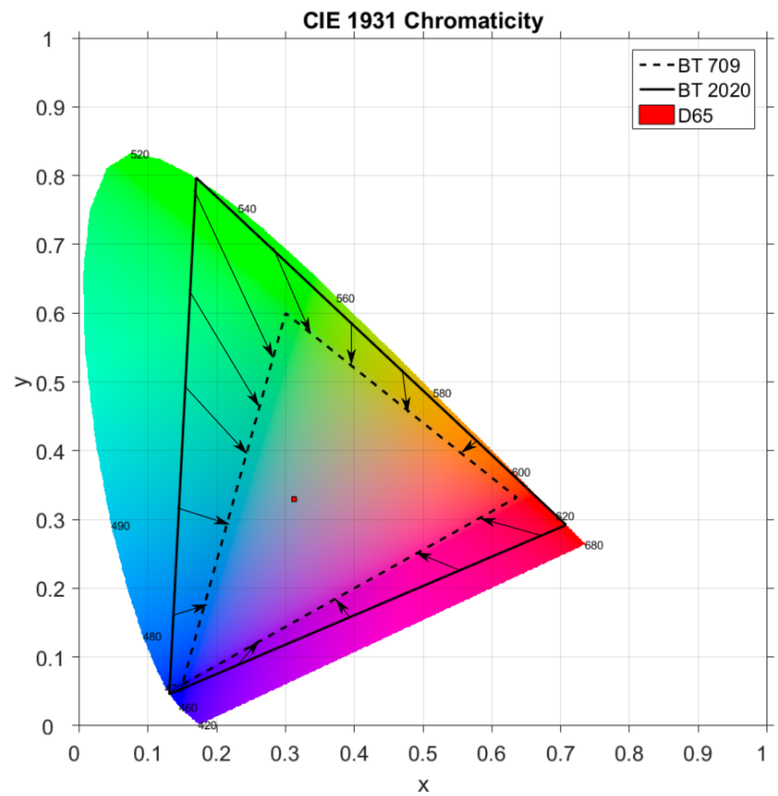

Figure 1. CIE 1931[2] xy chromaticity diagram with the BT.709[3] and BT.2020[1] color gamuts. Arrows illustrate gamut mapping.

source gamut inside a target gamut. This projection can be performed in any color space. Indeed, many color spaces exist with different characteristics such as perceptual uniformity, hue linearity, etc. The efficiency of the gamut mapping depends on both the used color space and the chosen projection technique.

In this article, we evaluate the distortion introduced by gamut mapping when combining two different projection techniques with six color spaces. We also evaluate the distortion that will be introduced by letting the display wrongly interpret the content as being in BT.709, or converting it to BT.709 and clipping code value to their maximal range. The CIEDE2000[4] (ΔE_{00}) objective metric is used to assess this distortion between the original and mapped color information. Through this study, we aim at determining which combination of color space and projection performs the best when mapping all possible UHD color code values to HD code values. We also reports which specific colors are the most affected ones by each gamut mapping combination.

The remainder of this article is organized as follows: Section 2 gives some background on what is a color gamut, presents the characteristics of the color spaces and describes the projections. Section 3 gives the methodology employed. In Section 4, we present and discuss both objective metric results along with some example of color artifacts that gamut mapping can introduce. Finally, Section 5 concludes this article.

2. BACKGROUND ON GAMUT MAPPING

2.1 Color Gamut

A gamut is a subset of the visible colors that a display can show or that a camera can record and it is defined by a white point, a bit-depth and a set of primaries (usually three: Red, Green, Blue). Although many different color gamuts exist, in this article we focus only on the BT.2020[1] and BT.709[3], represented by the two triangles in Figure 1. For both gamuts, the white point is defined by the D65 illuminant and the primaries correspond to each corner of the corresponding triangle.

Set	xyY color space	R'G'B' (BT.2020 10 bits)	R'G'B' (BT.709 8 bits)
A	x = 0.329 y = 0.230 Y = 0.636	R' = 324 G' = 750 B' = 790	R' = 10 G' = 200 B' = 200
B	x = 0.147 y = 0.158 Y = 0.344	R' = 10 G' = 200 B' = 200	R' = -29 G' = 56 B' = 51

Table 1. xyY values and the associated R'G'B' values in both BT.709 and BT.2020 gamuts.

Any specific chromaticity value [x, y] for a luminance level Y can be represented by a positive weighted average of the three color primaries (R', G', B' for both standard) as long as this value lies inside the corresponding triangle. Since the BT.709 and BT.2020 have different primaries, a given chromaticity value and luminance level [x, y, Y] will not correspond to the same R'G'B' values in both gamuts. This is illustrated in Table 1 with two different sets of values. The first set (A) corresponds to a position that is inside both BT.709 and BT.2020 gamuts. Thus, it can be represented by a positive weighted average of the R'G'B' primaries. However, the second set of values (B) lies outside the BT.709 gamut and hence cannot be represented using a positive weighted average (a negative value appears).

Table 1 outlines two issues when addressing HD displays using UHD content:

- the same BT.2020 and BT.709 R'G'B' code values do not correspond to the same color information, thus direct interpretation by the display will result in altered colors,
- out of gamut colors will result in negative values when projected in the BT.709 gamut. Since pixels are represented using positive integer values that depend on the chosen bit-depth (8 bits for BT.709 and 10 bits for BT.2020), negative values cannot be represented.

To resolve both problems, color code values need to be converted from the source gamut (i.e. BT.2020) to the target gamut (i.e. BT.709) and out of gamut colors are required to be projected inside the target gamut.

2.2 Color Spaces

Gamut mapping can be performed in different color spaces. This subsection describes the characteristics of the color spaces used in this work. There are several color spaces with different purposes and applications. In our study we distinguish two types of color space representation: primary based and luminance/chrominance decomposition. In primary based color spaces, a weighted average of color primaries (typically Red, Green and Blue) is used to achieve a specific color. Note that RGB color channels are usually perceptually encoded and denoted as R'G'B'. The luminance/chrominance decomposition aims at decorrelating the luminance channel (usually denoted Y) from the chromaticity plane. The chromaticity plane allows representing a color using two chroma values (C1 and C2) that can correspond to Cartesian coordinates or to perceptual attributes (for example hue and saturation).

In 1931, the Commission Internationale de l'eclairage (CIE) standardized the CIE 1931 XYZ color space[2], which encompasses the full visible spectrum. Since, in the XYZ color space, X and Z are highly correlated with Y, the CIE xyY color space was derived by normalizing two components using the sum of all three components. The [x, y] chromaticity diagram, plotted in Figure 1, is the most common way of referring to a specific color value. However, this color space is not really perceptually uniform. A color space is defined as perceptually uniform if a difference in value anywhere in the color space corresponds to the same difference in perception. This property is illustrated by the MacAdams ellipses[5], which predict when two different color values will be differentiable by a human observer. Figure 2 (a) represents these ellipses in the CIE 1931 [x, y] chromaticity diagram. Dots in the center of ellipses represent the reference color while ellipses outline the smallest difference of values in every direction before a human observer would rate those two colors as different. In an ideal perceptually uniform color space, all ellipses would be circles and have the same radius as shown on Figure 2 (b).

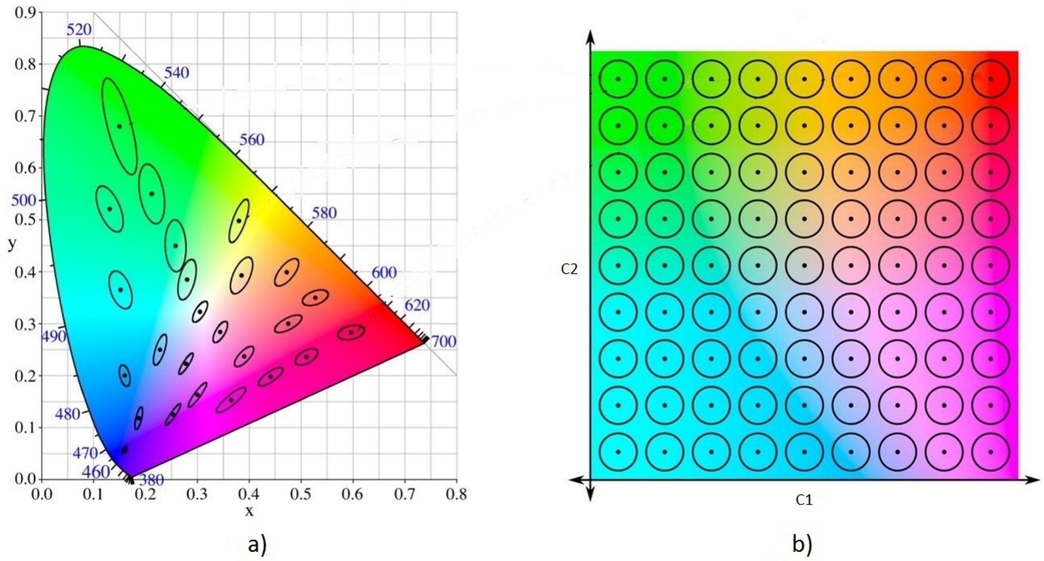

Figure 2. Representation of the MacAdams ellipses, in the CIE 1931 xy[2] chromaticity diagram (a) and in an ideal perceptual uniform chromaticity plane (b). The size of the ellipses in the CIE 1931 has been increase 10 times. Figure courtesy of Henrich et al.[10].

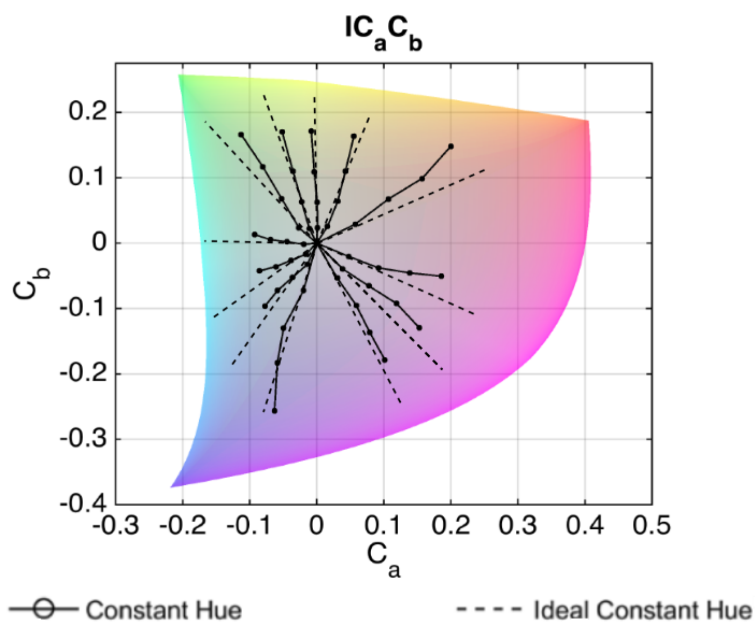

Figure 3. Hue lines in IC_aC_b. The ideal hue lines were added to show that the theoretical hue is constant along any lines staring from the white point and are solely used for illustration purpose. Figure courtesy of Froelich et al.[9].

Based on the work of MacAdam[6], the CIE 1960 UCS (Uniform Chromaticity Space) was standardized. This color space does not define a luminance channel but only describes a chromaticity plane known as [u, v]. That is why several versions of the [u, v] chromaticity plane exist such as CIE YUV, CIE Yuv and CIE 1976 L*u*v* (commonly referred to as CIELUV). In 1976, the CIE also defined the CIE 1976 L*a*b* color space (commonly referred to as CIELAB) as a further attempt at perceptual uniformity[7]. There is actually no consensus in the colorimetry field on which of the CIELAB or CIELUV is the most perceptually uniform.

Recent work on colorimetry focuses on constant hue lines[8]. Constant hue lines means that any straight line from the white point to an edge of the visible gamut should have the same hue, with only the saturation changing

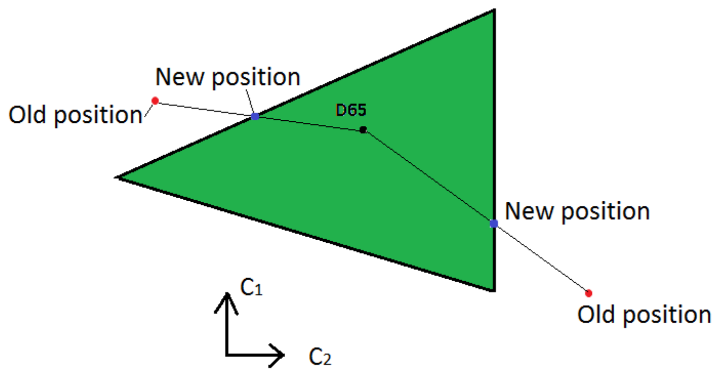

Figure 4. Illustration of the *TWP* (*Toward White Point*) projection. Chroma values (C1, C2) lying outside of the gamut (green triangle) are projected to the intersection between the gamut's boundary and the segment connecting the white point (D65) to the original chroma values.

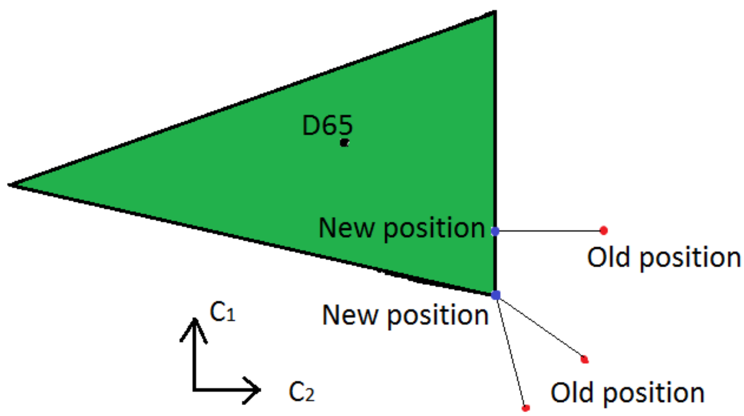

Figure 5. Illustration of the Closest projection. Chroma values (C1, C2) lying outside of the gamut (green triangle) are projected to the coordinates that corresponds to the smallest Euclidean distance on the chromaticity plane.

(see Figure 3). As the human eye is particularly sensible to hue changes, such a property of color space can greatly simplify color processing. This tendency led to the creation of a new color space, the IC_aC_b[9].

To summarize, there are several color spaces because different color processing procedures require different color space attributes. In this evaluation we study how color spaces, presented in this section, impact the quality of gamut mapping.

2.3 Projection Techniques

For gamut mapping, we use two common projection techniques: Toward White Point (TWP) and Closest. The TWP projection technique was introduced by Yang et al.[11] but its application was only tested with a single color space (CIELAB). This projection technique aims at keeping the theoretical hue unchanged while altering only the saturation. To this end it maps out-of-gamut colors to the intersection between the gamut boundaries and the line segment that links the white point and source color value as illustrated in Figure 4. The Closest projection technique, on the other hand, tries to minimize the Euclidean distance between the original color and the mapped color by mapping out-of-gamut colors to the closest possible position inside the gamut (see Figure 5). Thus it is expected to perform well with color spaces that are highly perceptually uniform.

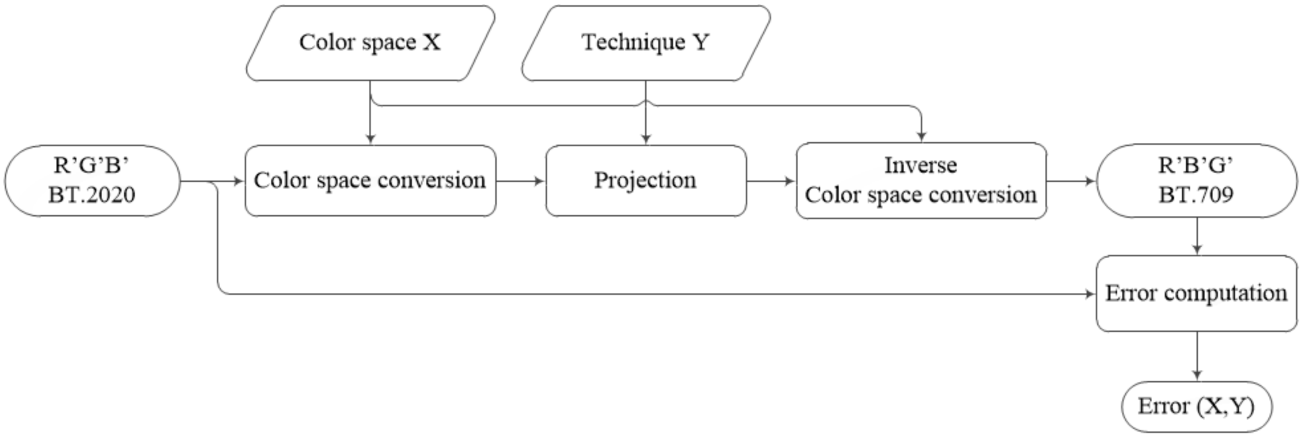

Figure 6. Proposed evaluation workflow

3. METHODOLOGY

To evaluate the efficiency of different projection techniques across color spaces, we propose the workflow shown in Figure 6. According to this workflow, the input pixel (represented by R'G'B' code values in the BT.2020 color space) is first converted to the selected color space and the projection technique is applied. Then, the mapped pixel is converted to R'G'B' code values in the BT.709 color space. Finally, the error is computed using an objective metric between the input and the mapped pixel. In our study, the ΔE_{00} objective metric is utilized as it is currently used in MPEG standardization activities. This metric is based on a Euclidean distance in the CIELAB color space[12]. To compensate for hue changes in the blue region as well as a lightness non-uniformity, the ΔE_{00} is calculated as a weighted sum of Euclidean distances over three different perceptual attributes[4]. This metric is normalized so that it returns a value of one at the just noticeable difference, that is to say when the difference between two colors is barely noticeable. Note that above one this metric only provides an indication as to which mapped color is the closest to the original.

We have limited our study to alterations in the chromaticity plane solely, as changing the luminance channel along with the chromaticity value usually results in poor results[11,13].

In addition to evaluating different projection techniques across color spaces, we also investigated two special cases that can occur during color mapping: *R'G'B' Clipping* and *Wrong Interpretation*. *R'G'B' Clipping* corresponds to converting BT.2020 code values to BT.709 ones using ITU-R Recommendation BT.2087[14]. This conversion results in out of gamut colors to be coded in negative or too high values. Since these values cannot be processed by the display, they are simply clipped to 0 or the maximum possible value. *Wrong Interpretation* is when no gamut conversion is performed. Thus, BT.2020 code values will be interpreted as BT.709.

4. EXPERIMENT RESULTS & DISCUSSION

4.1 Overalll Results

In our first experiment, we evaluate which gamut mapping performs the best when mapping all combinations of BT.2020 R'G'B' code values using 10 bits (1,073,741,824 colors) to BT.709. The main advantage of using such an array is that every possible color will be tested and each one will have the same weight when measuring the mean error. This experiment compares 14 methods: 12 combinations between two projection techniques (*TWP* and *Closest*) and six color spaces (CIE xyY, CIE Yuv, CIE Yuv, CIE L*u*v*, CIE L*a*b* and IC$_a$C$_b$) along with the *R'G'B' Clipping* and *Wrong Interpretation* cases. Table 2 summarizes the results.

From these results, the following observations can be made:

- The projection technique *TWP* performs better than the *Closest* for all of the tested color spaces, except the IC$_a$C$_b$ color space,

Combination Color Space + Projection		
Color Space	***TWP***	***Closest***
xyY	4.86	4.90
Yu'v'	4.86	4.94
Yuv	4.86	5.16
CIELUV	4.85	4.94
CIELAB	4.46	4.69
IC$_a$C$_b$	4.89	4.75

Special Gamut Mapping Cases	
R'G'B' Clipping	4.53
Wrong Interpretation	7.3

Table 2. Results of the different combinations using the ΔE_{00} metric.

- The CIELAB space achieves the lowest distortion for both *TWP* and Closest techniques,
- The *R'G'B' Clipping* performs surprisingly well, it is better than any *Closest*, but is still outperformed by the *TWP* projection in the CIELAB space,
- Allowing the display to wrongly interpret the content's gamut leads to the worst results,
- The *TWP* projection gives the same results for Yu'v', Yuv and CIELUV spaces. This can be explained by the fact that these three color spaces are linear transformations of one another and *TWP* is also a linear transformation.

Overall, the performance of the *TWP* projection in the CIELAB color space provides the lowest mean error. However, the selected metric is based on the Euclidean distance in this color space and could, therefore, favor this color space. Finally, the difference between all combinations is not as significant as expected. The insignificant difference between these results does not justify the computations required to convert to an alternative color space, thus favoring the *R'G'B' Clipping*.

4.2 Color Dependency Result

The results presented in Table 2 correspond to an average over all combinations. Analyzing the distribution of these errors over the chromaticity plane may provide different information. Indeed, depending on the type of content, different gamut mapping might be preferred, for example the accuracy of green colors for a football game. Thus, in our second experiment, we compare the distribution of the errors over the BT.2020 color gamut to identify which colors are the most distorted by the different gamut mapping techniques.

Figures 7, 8, 9 plot the errors introduced by both *TWP* and *Closest* projections in xyY, CIELAB, IC$_a$C$_b$ color spaces as well as the *R'G'B' Clipping*. From these results the following observations can be made:

- *TWP* projection results in having the maximum error close to the corners of the triangle which correspond to highly saturated colors unlikely to be found in most natural scenes,
- *TWP* projection in the IC$_a$C$_b$ color space results in very high error in the blue colors (refer to Figure 1 for the location of each color). This error corresponds to a change of hue as illustrated in the first three lines of Table 3. Note that changes in the hue ($|\Delta H|$) affect the ΔE_{00}, while the other two attributes do not impact this value,
- *TWP* projection in the xyY color space results in higher error at the red corner. Again, a large hue shift is the main cause for this higher distortions as illustrated in Table 3,
- *Closest* projecting results in smaller error at the corners than the *TWP* one, especially at the green corner,
- *R'G'B' Clipping* values results in a similar distortion pattern as the Closest projection. This can be explained by the fact that R'G'B' Clipping corresponds to a Closest projection in the R'G'B' color space,

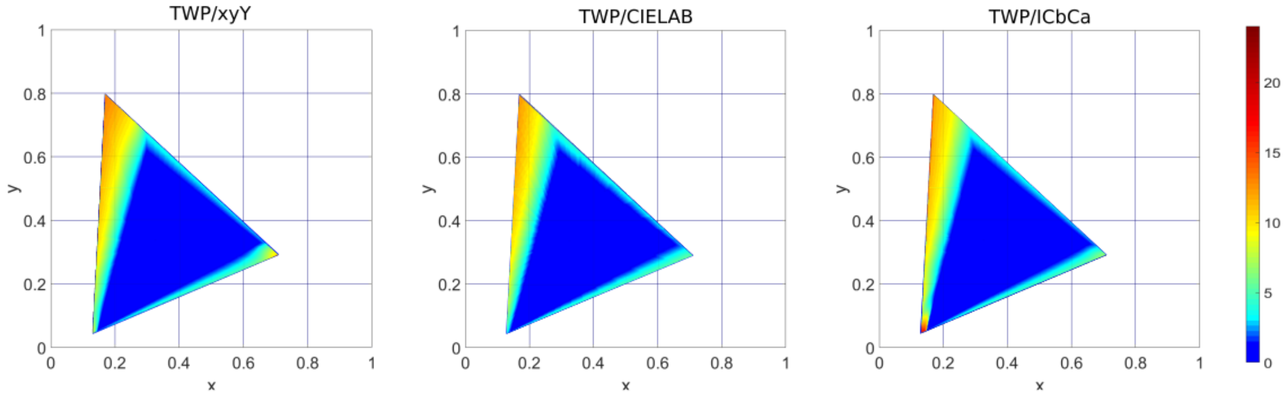

Figure 7. Distribution of the ΔE_{00} error for the *TWP* projection in different color spaces. The distribution is plotted in the CIE 1931 xy chromaticity plane with $Y = 0.06 \cdot Y_n$

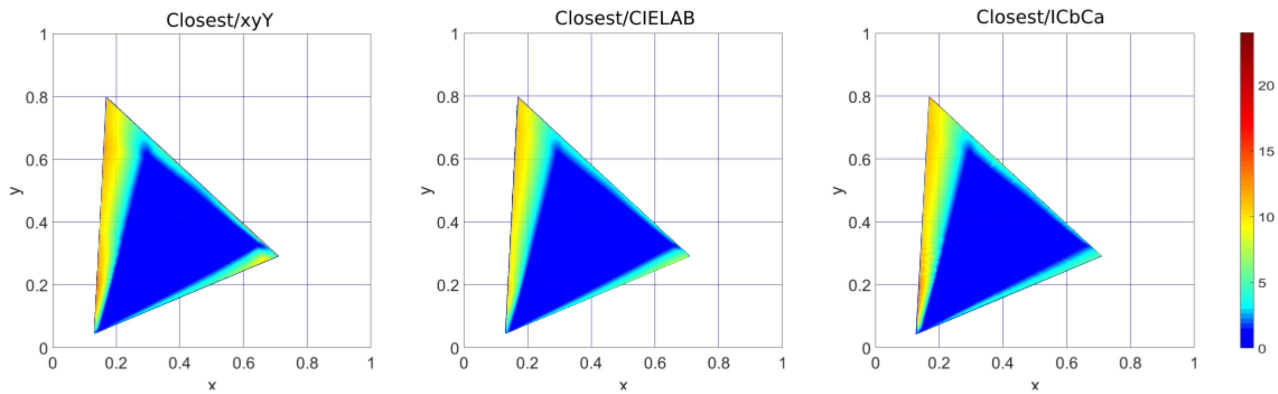

Figure 8. Distribution of the ΔE_{00} error for the *Closest* projection in different color spaces. The distribution is plotted in the CIE 1931 xy chromaticity plane with $Y = 0.06 \cdot Y_n$

4.3 Illustration of Gamut Mapping Color Artifacts

In our two first experiments, we measured color distortion using the ΔE_{00}. However, ΔE_{00} only predicts if a difference is visible between two colors, without taking into account the impact of factors such as visual masking and saliency. Furthermore, since the relative errors between techniques are very small, it is important to test the results of gamut mapping on natural images and not color patches.

Figure 10 illustrates the visual distortion introduced by different gamut mapping techniques for a natural image. Since displaying BT.2020 content is not possible, gamut mapping is performed between the BT.709 and a smaller gamut, which is obtained by applying the same matrix transformation to transform the BT.2020 gamut to the BT.709.

Figure 10 suggests that the results achieved by using different mapping algorithms are almost visually identical. Only a slight contrast loss is visible in the red feathers. Indeed, for most tested images, there is no noticeable difference between the different mapping algorithms.

Figure 11 illustrates another comparison between the *TWP/CIELAB* and *R'G'B' Clipping*. Note how using the *TWP/CIELAB* mapping helps preserving the contrast information. Furthermore, *R'G'B' Clipping* results in a hue shift as the red and yellowish red pixels look similar.

Finally, Figure 12 demonstrates the issues with Wrong interpretation, i.e. when BT.2020 code values are interpreted as BT.709. Low saturated images such as the ones presented in Figure 12, are mostly unchanged by the *TWP/CIELAB* mapping since few are out of gamut values. However, *Wrong Interpretation* changes all colors.

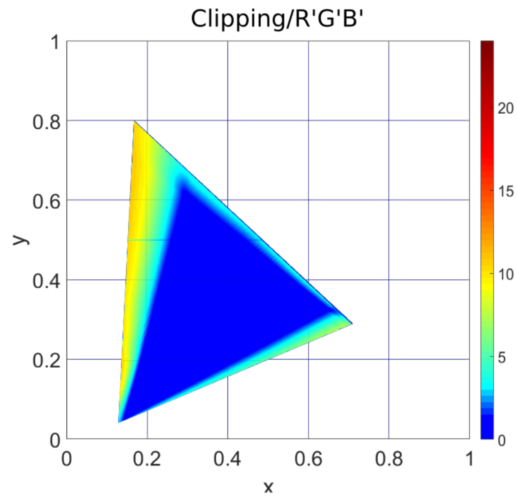

Figure 9. Distribution of the ΔE_{00} error for the *R'G'B' Clipping*. The distribution is plotted in the CIE 1931 xy chromaticity plane with $Y = 0.06 \cdot Y_n$

Projection	**Color (R', G', B')**	ΔE_{00}	$\lvert\Delta L\rvert$	$\lvert\Delta C\rvert$	$\lvert\Delta H\rvert$
TWP/ $\boldsymbol{IC_aC_b}$	Blue (0, 0, 1)	19.31	1.2	118	48.1
TWP/CIELAB	Blue (0, 0, 1)	3.9	0	26.9	0.76
R'G'B' Clipping	Blue (0, 0, 1)	4.17	4.9	9	1.72
TWP/ $\boldsymbol{IC_aC_b}$	Red (1, 0, 0)	16.05	0	58.8	32
TWP/CIELAB	Red (1, 0, 0)	6.41	0	44.5	0.86
R'G'B' Clipping	Red (1, 0, 0)	7.83	7.69	30.69	1.41

Table 3. Details on the ΔE_{00} metric characteristics that explain the difference in distortion between color spaces.

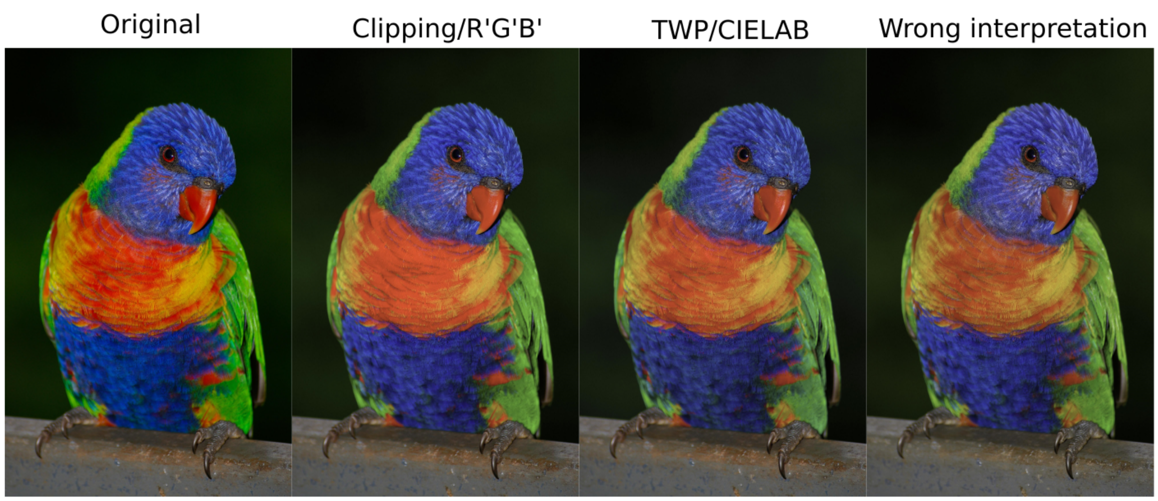

Figure 10. Original image versus different gamut mapping results: for a typical image.

To summarize, even if for most images *R'G'B' Clipping* provides adequate results (see Figure 10), highly saturated images can benefit from using a perceptual color space such as the CIELAB (Figure 11). Furthermore, averaging ΔE_{00} over a full picture may not be an accurate metric as Figure 11 images have similar mean ΔE_{00} (5.10 for *TWP/CIELAB* and 5.51 for *R'G'B' Clipping*). Finally, bear in mind that results showed in this section do not correspond to an actual BT.2020 to BT.709 conversion. Tests involving upcoming displays that can cover a higher proportion of BT.2020 will be needed in the future to evaluate subjectively the impact of color spaces for gamut mapping.

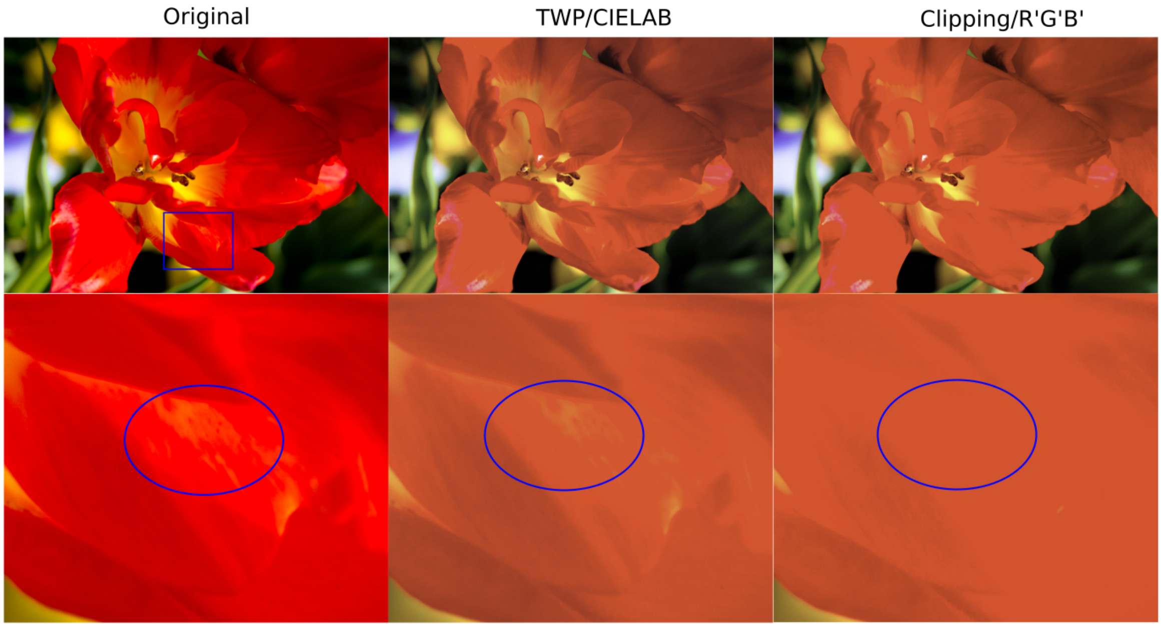

Figure 11. Illustration of loss of contrast contrast when performing *R'G'B' Clipping* on a highly saturated image. The bottom part corresponds to a zoom on the blue rectangle position.

Figure 12. Illustration of the unnecessary color distortion applied when the gamut is wrongly interpreted.

5. CONCLUSION

The aim of gamut mapping algorithms is to adapt the colors of any content to the limited capabilities of a television. An efficient mapping should distort as little as possible the perceived colors and to an extent the artistic intent. In this article two projections were used to map color patches in six colors spaces, giving twelve gamut mapping algorithms. Clipping R'G'B' code values and Wrong Interpretation of the BT.2020 gamut have also been tested.

Results show that the difference between gamut mapping algorithms is not as significant as expected. Moreover, the mapping which provides the smallest average error fails to give the smallest error for each specific color. These results indicate a preference of using *R'G'B' Clipping* as it gives similar mean ΔE_{00} error with a simpler implementation. However, tests with selected images demonstrate that it can also result in loss of contrast in highly saturated areas.

This study hints that future works may increase the efficiency of gamut mapping. For example, that may be achieved by selecting the combination that provides the lowest error for each color code value. Furthermore, psychophysical tests on wide color gamut displays need to be performed to design a color metric with higher accuracy than the ΔE_{00}.

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