1. Introduction

In today’s technology, many methods are developed for achieving High Dynamic Range (HDR) images (high quality image) such as: increasing the sensors number of pixels, taking several images with different light exposures intervals, taking several images taken from different angles (small), etc. But, in order to see an HDR image, the technology must supply a high-end device with large number of bits per pixel (otherwise, it doesn’t matter how accurate the HDR maps may be)
The author target is to map the HDR images into a Low Dynamic Range (LDR) devices (such as common computer monitors with 8 bits per RGB, printers, etc.) in an accurately and faithfully reproduced manner compared to the original scene, **and in low complexity solution**.
Two broad categories of technology exist for this purpose.

- Tone Reproduction Operator (TRO) – involves spatial manipulation (local technique) and is considered “high complexity” solution.
- Tone Reproduction Curve (TRC) – a technique that uses monotonic mapping function to transfer world luminance to display luminance. This technique essentially works on the overall pixel’s histogram (Global technique) to optimize the power and quantization levels. These techniques are considered low complexity solutions.

We think that the best solution should include both local and global categories as exist in the human eye system (as demonstrated in Retinex theory). But as we noted above, the article’s target is to find a low complexity solution for real time applications (such as HDR video) and thus doesn’t involve any spatial processing.
The author notices that the mapping from luminance to brightness of each person is different, thus the commonly used TRC methods will not give the best image reproduction. To solve this, the author suggested relying on the user to assist with the reproduction. For this to work, a simple tool should be defined such that assist the user achieving (with a small effort - small search space) the best image reproduction.
Thus, two configuration parameters were determined to be controlled by the user – an adaptive global luminance-mapping operator which compress the luminance of the high dynamic range image and simultaneously set the overall brightness of the reproduction by changing a single number. The output of this first sub-operator is then adjusted to final display luminance in such a way that changing another number can easily control the “right amount” of detail and contrast in the reproduction. In the next section we will describe in further detail how those operators are built and their effect on our LDR image.

2. Model

The paper presents a reproduction curve-based mapping for the fast visualization of high dynamic range images. Since Image reproduction is a highly subjective process, the writers aimed to include as few adjustable parameters as possible, with equal importance. Furthermore, the parameters should have a clear, intuitive, and straightforward relationship with the appearance of the mapped images to guide the users to adjust the parameters.

Firstly, the luminance signal is calculated as:

$$L = 0.299R + 0.587G + 0.114B \qquad (1)$$

Where R, G and B refer to the RGB channels of the HDR input image.
As can be seen in Eq.1, the luminance signal has a bias towards the green channel. This, as taught in class, is because the photopic luminance efficiency - a measure of how well a light source produces visible light, has a maximum at a wavelength of 555 nm (green) which translates to wavelengths closer to green having bigger impact on the luminance.

The tone mapping operator that consists of two sub-operators:

1) **Adaptive Luminance Mapping -** compress the luminance of high dynamic range image and simultaneously set the overall brightness of the reproduction.
2) **Adaptive Histogram Adjustment –** adjusts the final display luminance to affect contrast and the amount of detail in the reproduction.

Adaptive Luminance Mapping
As a first step, they used the following function to compress the luminance of the high dynamic range image ***I*** to

display luminance $\boldsymbol{D}$:

$$D(I) = (D_{max} - D_{min}) * \frac{(\log(I + \tau) - \log(I_{min} + \tau))}{(\log(I_{max} + \tau) - \log(I_{min} + \tau))} - D_{min} \qquad (2)$$

where I_{min} and I_{max} are the minimum and maximum luminance of the scene, and D_{max} and D_{min} are the minimum and maximum luminance of the visualization devices. and τ is set to:

$$\tau = \alpha(I_{max} - I_{min}) \qquad (3)$$

Eq.2 ensures that the maximum and minimum luminance values of the scene are respectively mapped to the maximum and minimum luminance of the visualization device. Adjusting τ via α will appropriately tune the overall brightness of the reproduced image. Using different α values can help introduce more brightness to the image according to the user's liking.

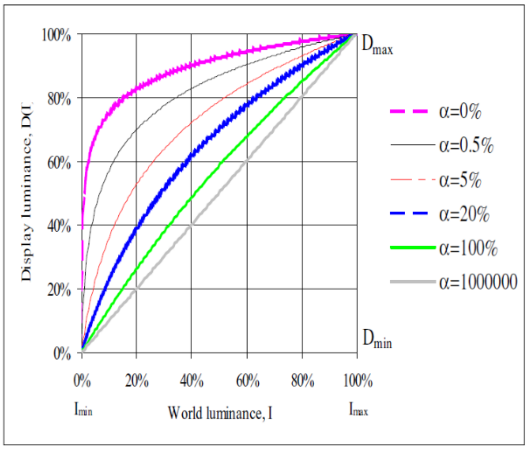


Figure 1: The global luminance-mapping curve of (2) for different values of α

As can be seen in Fig.1, the global luminance-mapping follows Weber-Fechner law which taught in class states that the intensity of our sensation increases as the logarithm of an increase in energy rather than as rapidly as the increase. And in our case, The eye senses brightness approximately logarithmically over a moderate range

Figure 2: A high dynamic range image mapped using Equation (2) with different values of τ

Although, the overall brightness of the mapped image can be set appropriately using α, for most of the cases, the adaptive luminance mapping function produces images that appear to not have sufficient details and appear low contrast. Looking into the histograms revealed a typical characteristic of these histograms is that all have a narrow shape. To tune the contrast and level of details, they used an additional sub-operator.

Adaptive Histogram Adjustment

The reason that rendering ***D***(***I***) for display will result in the lack of detail and contrast is caused by linear scaling. the range of ***D***(***I***) is divided into equal intervals, and pixels falling into the same interval are compressed to have the same display value. Linear scaling is done purely based on the pixel dynamic range without considering the image's pixel distribution characteristics. Consequently, too many pixels are squeezed into one display value, resulting in a loss of detail and contrast

A technique that considers pixel distribution is histogram equalization. This method divides the range of ***D(I)*** into N intervals based on the pixel distribution only. Within each interval, there is an equal number of pixels falling onto it.

Although histogram equalization mapping makes full use of the display dynamic range, it often introduces objectionable visual artifacts, while simple linear scaling of ***D(I)*** often results in the under-utilization of display dynamic range, which lead to the low contrast images. Fortunately, the drawbacks of each of the techniques is compensated by one another.

Therefore, the second operator takes the output of the first operator ***D***(***I***) as input and adjusts it to the display image using a curve that is between linear scaling and histogram equalization, as depicted in Fig.3

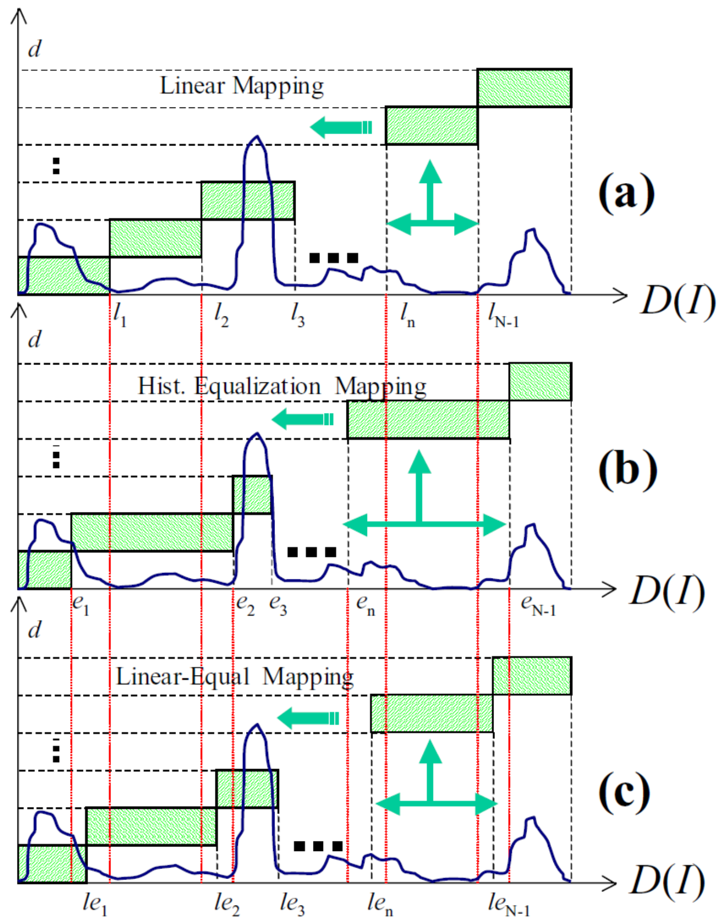


Figure 3: Mapping the output of D(I) for display. (a) Linear (b) Histogram equalization (c) The proposed sub-operator

The proposed sub-operator divides the luminance range into N (order of 100,000) intervals in such a way that the cuts should fall in between those of the linear scaling and histogram equalization. One way to achieve this is to map the image by optimizing following objective function with respect to le_k

$$E = \sum_{k=1}^{N-1}\left(le_k - \frac{k(D_{\max} - D_{\min})}{N}\right)^2 + \lambda \sum_{k=1}^{N-1}\left(\int_{D_{\min}}^{le_k} h(x)dx - \frac{k}{N}\int_{D_{\min}}^{D_{\max}} h(x)dx \right)^2$$

where *h(x)* is the histogram and λ is the Lagrange multiplier.

However, a straightforward numerical solution to optimize *E* may be difficult to obtain. Instead, they used a more intuitive approach to perform the mapping. With reference to Figure 3, for linear mapping, the luminance axis is cut at l_1, l_2, …, l_{N-1}. For histogram equalization, the luminance axis is cut at e_1, e_2, …, e_{N-1}. Their proposed operator cut the luminance axis at le_1, le_2, …, le_{N-1}, which satisfy following relation:

$$le_n = l_n + \beta(e_n - l_n) \qquad (4)$$

where 0≤ β ≤1 is a controlling parameter. If β = 0, the mapping is linear, β = 1, the mapping is histogram equalized. Setting 0< β <1, we control the mapping between linear scaling and histogram equalized in a simple and elegant manner.

After mapping, the images are rendered for display using following formula:

$$R_{out} = \left(\frac{R_{in}}{L_{in}}\right)^{\gamma} L_{out}\,, G_{out} = \left(\frac{G_{in}}{L_{in}}\right)^{\gamma} L_{out}\,, B_{out} = \left(\frac{B_{in}}{L_{in}}\right)^{\gamma} L_{out} \qquad (5)$$

where L_{in} and L_{out} are luminance values before and after compression, γ controls display color (setting it between 0.4 and 0.6 worked well).

3. Results

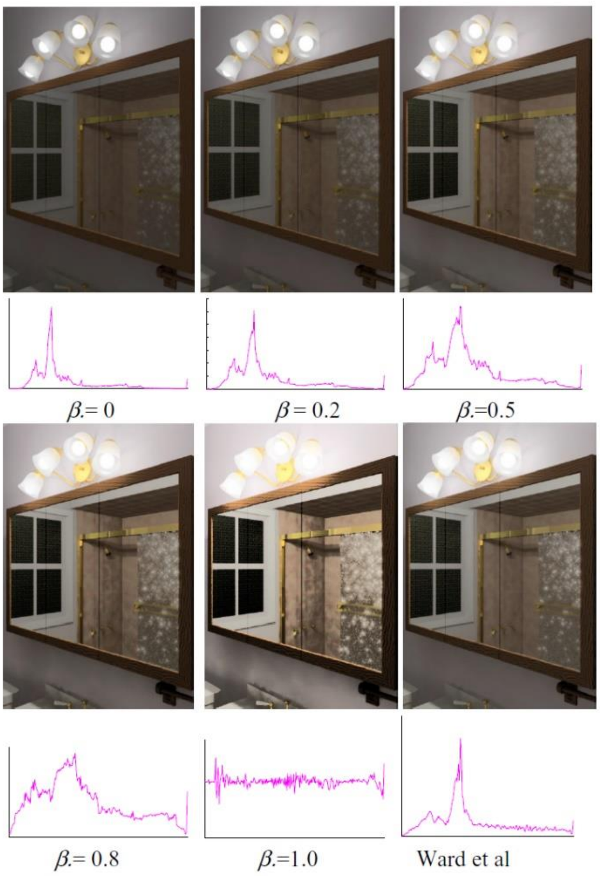


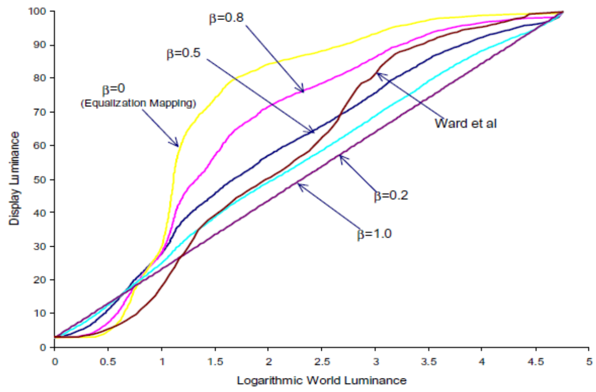
Figure 4: The Bathroom image mapped by the proposed algorithm using different β values

Experimental results have demonstrated that the proposed method can produce good results on a wide variety of high dynamic range images.
Figure 4 shows the result of a bathroom image mapped by the proposed tone mapping operator for τ=0 and various β values including histogram equalization (β=1.0), and the results of an operator presented in the paper "A Visibility Matching Tone Reproduction Operator for High Dynamic Range Scenes" by Ward et al. which applies histogram adjustment based on human contrast sensitivity.

As can be seen, setting different values of beta produces a wide variety of contrast levels and helps this operator handle different histograms shapes making it a versatile tool.

The image in Fig. 4 has very few very bright pixels which correspond to the area of the lamps and histogram equalization clearly compresses these pixels too aggressively, so does the method of Ward et al because this is essentially an approximate histogram equalization method in treating sparsely populated intervals.

This can also be seen in Figure 7 where a very short display luminance interval has been allocated to the very bright part of the world luminance by both the histogram equalization and Ward et al's method, while the proposed method is more flexible and by adjusting β, we can flexibly assign more display intervals to the very bright world luminance interval and retain more details in this area.



The proposed operator is related to the histogram adjustment technique of Ward et al in the sense that both manipulate the histogram. The reason that the method of Ward et al compresses the dynamic range in this interval so aggressively is because, the method is based on approximate histogram equalization (by accumulating pixel population) to produce its mapping curve, however, pixel population in this interval is sparse, the display produced in this region by the mapping curve will have low contrast and in such case the algorithm of Ward et al does nothing but follows histogram equalization mapping.

The proposed operator adds more freedom to adjust the display levels assigned to such sparsely populated intervals resulting in higher level of detail.

4. Discussion

The article proposes to let the user decide on the parameters utilization in order to get the best image reproduction. He does it by configuring a small number of control parameters such that the complexity of the user interface is considered relatively low. Also, spatial global reproduction is used to reduce the number of operations compared to local operator (applied on each pixel) which is considered a higher computation solution.
The author solution has a correct and intuitive design with good understanding that the gap from luminance to brightness is different for each person (each person has differences in the luminance processing), thus it makes sense to let each person optimize the parameters by its own.
Also, the understanding that low complexity solution is required in order to make it a user practical solution.

Still we think that both global and local solutions can be used for better results.
For example – several options for joint processing:

1. Applying global operations (such as histogram equalization) and after a local filtering for improving the contrast.
2. Applying local operations and after a global operation for improving the brightness.
3. Applying local operations and after using the article global algorithm with machine learning aided to optimize the contrast and brightness parameters.

The article compared its results to a different global operator which he showed better results compared to him. But he didn't compare him to local operator which we think will have the upper hand.
To conclude – we think that the article reached good results and with a practical solution. On the other hand, we think that further work can be done on the subject (as proposed above), that should include algorithms that are applied in the human eye system.

5. Code

We implemented the proposed operator for mapping high dynamic range images using Matlab. The implementation includes the following functions:

```
[Iout] = hdr_fast_tone_mapping(hdrImg,alpha,beta,gamma,nbins)
```

This function receives as input:

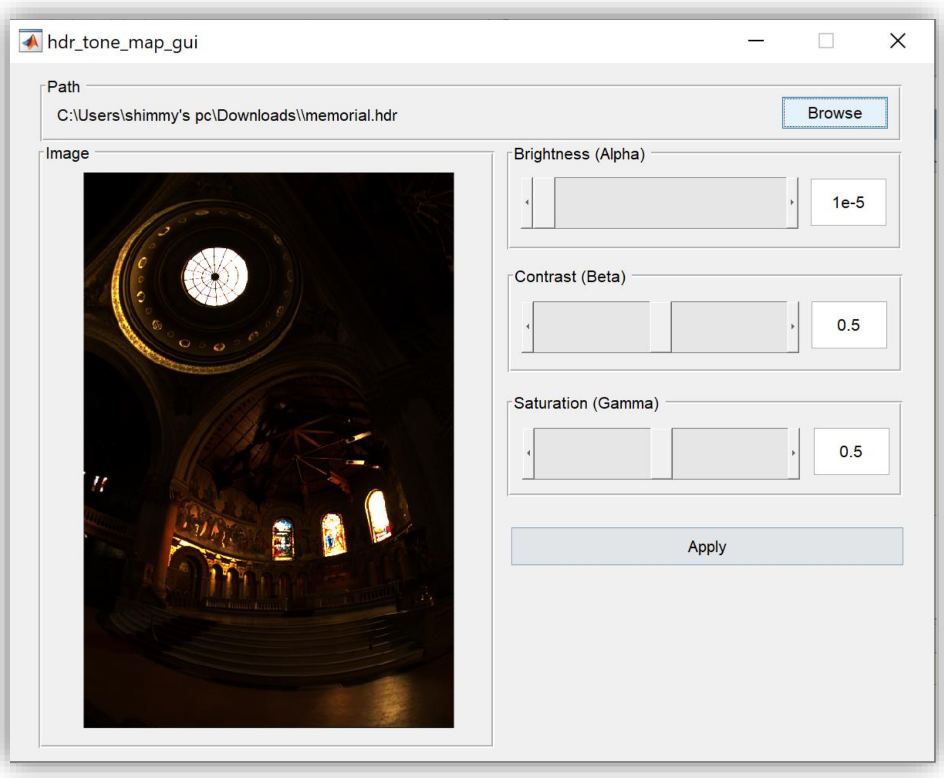
1) **hdrImg** – a HDR format image for mapping
2) **alpha** – float, a parameter for adjusting the overall brightness of the reproduced image in accordance with eq.2 and eq.3
3) **beta** – float, range 0-1, a parameter controlling the mapping ration between linear scaling and histogram equalizion. In accordance with eq. 4

4) **gamma** - float, range 0-1, a parameter for adjusting the overall saturation of the reproduced image. In accordance with eq. 5
5) **nbins** – integer, a parameter which sets the number of quantization levels of the luminance. Higher values will result in higher luminance resolution at the expanse of computation complexity.

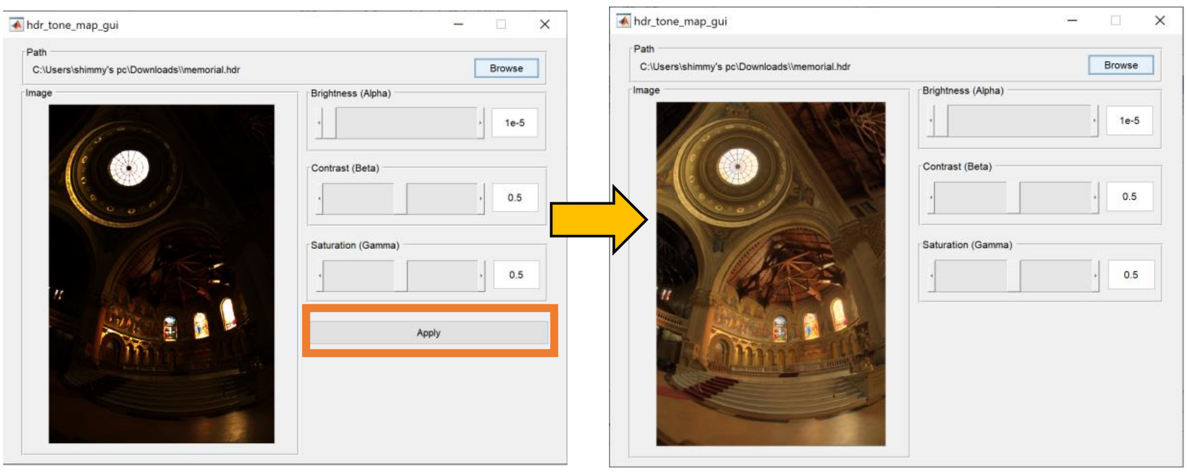
And returns **Iout,** the mapped input image using the proposed operator, as output.

Since the mapping of high dynamic range images is highly subjective process and to fully understand how each of the parameters – alpha, beta and gamma affect the output image, we designed a simple GUI which allows quick and easy change of the parameters and the display of the mapped image.

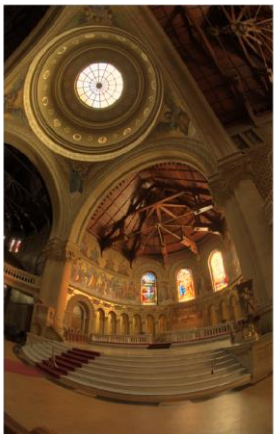
To use the GUI just run the function `hdr_tone_map_gui`:



The browse button lets the user load the input image (.hdr). The user can change the parameters – alpha, beta and gamma using either the sliders or the text box next to it. Once an image was loaded, or there was a change in configuration, the apply button will appear. Clicking the apply button will map the input image according the proposed operator:



Alpha (Brightness):



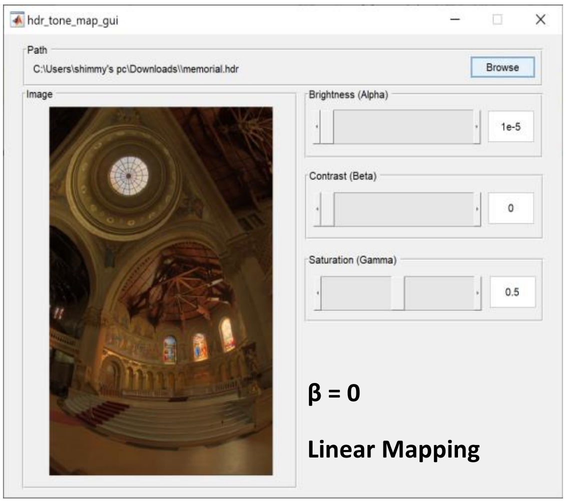
α = 1e-5

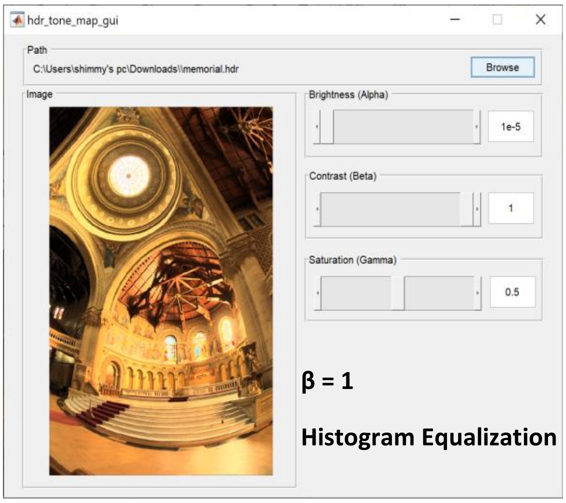
α = 1e-3

α = 1e-1

As can be seen above, lower values of alpha result in more dynamic range allocated to dark parts of the image. This is also with accordance with the global luminance-mapping curve in figure 1.

Contrast (Beta):





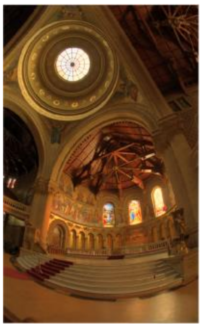
As can be seen above, setting beta to 1 result in a histogram equalized image while setting it to 0 results in linearly scaled image. Any value between 0-1 will balance between contrast and level of detail as the histogram equalization introduces contrast at the expanse of details while linear scaling preserves more details.

Saturation (Gamma):

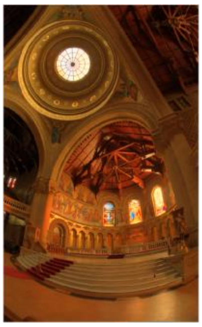
γ = 0

γ = 0.2

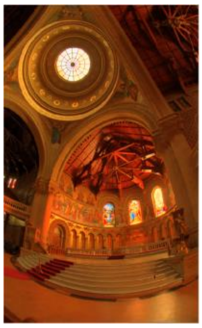
γ = 0.4



γ = 0.6



γ = 0.8



γ = 1

As can be seen above, higher values of gamma result in more saturated color. Setting gamma to zero results in the loss of vibrance and color.