Inverse Tone Mapping Operators Evaluation Using Blind Image Quality Assessment

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***Abstract*—Recently more and more researches work on reproducing real-world appearance images through LDR images using inverse tone mapping methods. Therefore, evaluation metrics to qualify the performance of inverse tone mapping operators (iTMO) are needed to understand the effect of important features such as nonlinearity. Most metric requires a reference ground truth to compare with the resulting HDR images. However, a reference HDR image may not be available or hard to verify as a ground truth. In this work, we propose a blind image quality assessment that measures test images without information from reference images. The blind image estimation method contains attributes of contrast, brightness, and colorfulness. The analysis results of contrast and brightness matches with that of the JND-based contrast analysis and human perception.**

I. Introduction

A. Motivation and recent work

Dynamic range of a scene or an image is the ratio of the maximum to the minimum luminance. Researches show that the luminance adaptation level for human visual system can achieve more than 1:10000, which is wider than the luminance range on the traditional digital displays. Significant process has been made in the development of HDR video sensors so that high dynamic range images and videos become available. The recent development of the OLED, LED, LCD and laser TV technology makes the ability to display HDR images or videos on these devices become important.

With the availability of the high quality display devices, the acquisitions of HDR images or videos become more and more urgent. Conventional image acquisition produces low dynamic range images because of the limitations of bit resolution. As a result, virtually any image captured by a conventional imaging system may end up being too dark in some areas or possibly saturated in others. HDR acquisition technologies to capture high dynamic range (HDR) images with a low dynamic range (LDR) detector have been developed.

The most common approach is to sequentially capture multiple images of the same scene using different exposures. This kind of approaches have been developed by Mann and Picard [1][3], Debevec and Malik, [2][4], Nayar and Mitsunaga [3][5]. The above methods are only suitable for producing static scenes. Using multiple detectors or sensors to capture a scene simultaneously has been investigated. This kind of approach can produce HDR images in real time. Besides, objects in the scene and the imaging system are free to move during the capture process. However, the major problem of such technique is the high cost of overall systems since multiple sophisticated detectors are required at the same time.

Despite the increasing availability of HDR content, legacy LDR images and videos represent the majority of content in the near term. Other researches work on reproducing real-world appearance images through LDR images. The problem of estimating HDR images from LDR photographs or Inverse tone mapping operation (iTMO) has also recently received attention.

Most current iTMO algorithms are composed of two main steps, the global inverse tone mapping and the local optimization. The global inverse tone mapping extends the luminance range and contrast of the LDR image through a curve function. Rempel et al. [5] present a linear scale curve as their real-time global iTMO algorithm. Akyuz et al. [6] evaluate several iTMO curves from two perceptual experiments and claim that applying simple gamma curves to LDR images produces satisfactory results on HDR displays. Similar to Akyuzs experiments, Masia et al. [8] proposed several iTMO evaluation methods. Different exposure conditions are applied to the scene and they find that LDR images with gamma correction result in good visual quality. There are several complex inverse mapping curves presented to gain better performance of luminance and contrast expansion. Meylan et al. [7] introduce a piecewise tone scale function and the shape of the scale function depends on the segmentation of the input images into its diffuse and specular components. Banterle et al. [9] propose the inverse version of Reinhard et al.s photographic operator as the iTMO curve. Ke et al . [10] adopt inverse S-shaped curves to extend the contrast of brighter and darker area.

The target of local optimization for iTMO algorithms is to boost luminance and contrast in saturation area of LDR input images. Banterle et al. [9] estimate the high luminance area of an input image by using median-cut algorithm and subsequently apply a density estimation to generate an Expand-map in order to extend the range in the high luminance areas using an inverse Photographic Tone Reproduction operator. Banterle et al. [11] employ a temporal density estimation with automatic parameters estimation. This helps to expand the dynamic range smoothly and reduce the flickering. The use of bilateral filter improves the expand map in reducing halos and enhancing contrast around edges. With the edge-stopping function, Gaussian blur and image pyramids, Rempel et al. [5] introduce a procedure for smooth brightness enhancement of saturated regions to achieve computation efficiency. By adding details to under-exposed or over-exposed region, an interactive texture synthesis approach is proposed for increasing detail and producing higher dynamic range image effectively [12]. However, this method requires users to indicate the foreground or background of images manually. Didyk et al. [13] use a semi-automatic classifiers for clipping the light sources and specular reflections of video sequences, then enhance bright elements by stretching the contrast of those regions.

Most proposed iTMO algorithms are evaluated by two types of quality assessment methods. One is through perceptual experiments by asking people reviewing various inverse tone mapped images against each other either on HDR display monitors or on LDR display after the same tone mapping. The evaluation criterion is based on visual appeal or realism. Since the original HDR images are not used in the comparison, these studies only reveal the relative rankings of tone-mapping algorithms. The other is quantitative analysis by comparing difference of pixel intensity or contrast values between test and reference images. Mantiuk et al.s visible difference predicator (VDP) [2004b], an HDR variant of the original VDP work by Daly et al. [Daly 1993] is a widely adopted evaluation metric that detects difference between two images on a side-by-side comparison of individual image regions. The VDP simply indicates visual difference regions but it is not suitable for identifying the exact shape of the differences. Akyuz et al. propose the dynamic range independent quality assessment novel image quality metric capable of operating on an image pair with arbitrary dynamic ranges. They utilize a model of the human visual system, and define visible distortion based on the detection and classification of visible changes in the image structure.

Based on those evaluation metrics, many researchers work on the performance analysis of inverse tone mapping operators. Akyuz et al. [6] report two psychophysical studies that a linear expansion from LDRI could represent good quality than several virtual HDRI from complicated method. Banterle et al. [9] present a psychophysical evaluation using the Dolby DR-37P HDR display. They let subjects compare the similarity of a paired virtual HDRI from several iTMOs and a referenced HDRI, the result of their work shows that virtual HDRI from nonlinear contrast enhancement curve might perform better than linear methods. Masia et al. [5]s evaluation work varies exposure conditions and they find that the quality rating in the dark images series are more stable than brighter one. They also claimed that the less visual quality on the HDR monitor were also less preferred when shown on LDR monitor.

Image quality assessment methods can also be classified in the following way: Full-reference (FR) metrics measure image quality depending on the visual similarity or fidelity between reference and test image. It is a standard and popular approach, but those metrics are limited when the reference image is not available. No-reference (NR) metrics, also called blind image quality assessment, estimate image quality without information from the reference image so it has wide range of applications. However, design NR metrics is difficult due to lack of data from the ground truth.

Traditional iTMO and TMO researches assess the image quality using subjective perceptual experiments or objective full reference image quality assessment metrics such as SSIM or HDR-VDP. However, for practical inverse tone mapping cases, it is hard to obtain the reference HDRI or comparing with real-scene HDR because those existing LDR contents are acquired earlier.

This work proposes a blind image quality assessment that measures test images without information from reference images. The blind image estimation method contains attributes of contrast, brightness, and colorfulness. The analysis results of contrast and brightness matches with that of the JND-based contrast analysis and the characteristics of iTMO curves. Compared with previous approaches, our evaluation metric provides valuable quality assessment results consistent with human perception and the computation complexity is much lower.

This paper is organized as follows. In section II shows the proposed evaluation framework. In section III introduces no-reference image quality assessment for iTMO evaluation works, and shows some experiment result. Finally, conclusions will be shown in the last part.

II. REFERENCE IMAGES AND PROPOSED EVALUATION FRAMEWORK

There are two type evaluation methods for estimating performance of iTMOs, Subjective methods such like perceptual experiments are usually used for image quality assessment, which let subjects compare the visual difference of test image and reference image, or rank some test images from different operators. Other evaluation methods are objective image quality assessment metrics, there are some models are built for analysis the difference of both test image and reference image.

To evaluate virtual HDRI from iTMO, there are reference HDRIs are prepared. Some of those reference HDRIs are from multi-exposed photographs and then rendering them to a high dynamic range by HDRI synthesis tools, another are scaled from input LDRI. Existing evaluation method which using HDR-VDP metric proposed by Mantiuk [15]. This work presents an innovative method which compares both test and reference HDRI in low dynamic range domain, both of them are applying photographic tone mapping operator as shown in fig.1.

Photographic tone mapping operator is judged one of subjective preference method of existing TMOs. [18, 19] Comparing important feature of test image to a real world scene, photographic tone mapping operator is consider keep more fidelity than other TMOS.[20] , those conclusions are useful and inspired.

We add another evaluate method that is compress test HDRI and reference HDRI to low dynamic range and compare some important attributes of image quality such as contrast, colorfulness, and brightness. Photographic tone mapping operator is used here for transform HDRI to LDRI, and there are some no-reference image quality assessment metrics are used for estimated the image attributes. More details are discussed in the following sections.

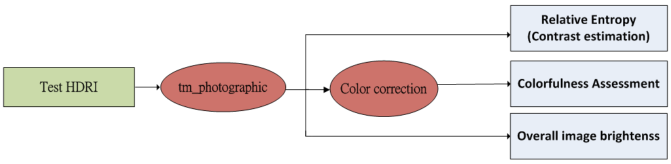

Fig. 1. Proposed iTMO evaluation frame work

III. BLIND IMAGE QUALITY ASSESSMENT

Overall image quality can be defined from many image attributes, such as brightness, colorfulness, contrast, and detail reproduction. M. Cadík et al.[29] introduced an evaluation method of TMOs using perceptual experiments and conclude an overall image quality function from four selected basic image attributes. In this section, we extend this evaluation approach with combination of some no reference image quality assessment methods and then introduced an innovative overall image quality assessment metric.

It seems designing NRQA metric is more difficult than FRQA metric when determining image quality without knowledge of the ground truth, however, there are still some related works for developing blind assessment model to estimate some important image attributes. This section adopts some classical and effective measurement approaches to access the image quality of the virtual HDRIs. Following are the details of those metrics.

Blind image quality assessment: brightness: To evaluate the brightness of overall image, we compute the key value of the test image based on Rechiard *et al.*'s log-average luminance approximation method.[30] Following is the formulation:

$$\bar{L_w} = exp(\frac{1}{N}\sum_{i,j} log(L_w(i,j)+\delta)) \tag{1}$$

Where $L_w(i,j)$ is the luminance at position (i, j), N is the total number of pixels in the image and is a small value to avoid the singularity that occurs if black pixels are present in the image. This model estimate the key of an image, which indicate the overall lighting condition, higher value means the brighter scene content.

Blind image quality assessment: contrast: We adopt relative entropy model introduced by [31] to measure the performance of image contrast, this model evaluate the amount of local detail. The formulation is depicted at eq.(2).

$$R_x = \log \frac{\sum_{x'\in W(x)} L_{x'}/N^2}{\left(\prod_{x'\in W(x)} L_{x'}\right)^{1/N^2}} \tag{2}$$

R_x is the relative entropy value for the pixel x, and W(x) is a set of neighboring pixels in the N by N window with centered pixel x. Every neighboring pixel in this window is denoted as $x\prime$. is defined as logarithmic form of arithmetic mean divided by geometric mean. Larger the R_x value indicates higher contrast in this area; the special cases are strong edges and detailed image region. When value is near to zero, it means there are smooth area around the pixel x.

To consider production of the unwanted noised due to contrast stretch, an average relative entropy to the noise level (RE/N) depicted in eq. (3) is used for evaluated the quality of contrast enhancement.

$$\text{RE/N} = \frac{\sum_x R_x/N}{\sum_i std(B_i)/N_B} \tag{3}$$

Where R_x is relative entropy of pixel x, as eq. (2), B_i is the ith block, and N_b and N are the total number of blocks and pixels respectively. $\sum_i std(B_i)/N_B$ is defined as noise level to estimate the probability of noise introduction.

Blind image quality assessment: colorfulness: Hasler *et al.*[32] introduced a model to quantify the perceptual quality of the color in image or videos. They designed an experiment for 20 subjects to rate the colorfulness for a set of 84 images, and concluded an effective metric to access the colorfulness, where image pixels is transformed to the CIELab color space. They also proposed a more efficient colorfulness assessment metric based on RGB color space, which is used in this thesis.

Assume test image is in the sRGB color space. First, compute the rg and yb color value using eq. (4). After that, apply the colorfulness metric which shows in eq. (5). Colorfulness estimation Mcol is weighted summation of the standard deviation σ and the mean value μ of the pixels in rg and yb color space.

$$\begin{cases} rg = R - G \\ yb = 0.5(R+G) - B \end{cases} \tag{4}$$

$$\begin{cases} M_{col} = \sigma_{rgyb} + 0.3 \cdot \mu_{rgyb} \\ \sigma_{rgyb} = (\sigma_{rg} + \sigma_{yb})^0.5 \\ \mu_{rgyb} = (\mu_{rg} + \mu_{yb})^0.5 \end{cases} \tag{5}$$

Table I shows the correspondence between estimated value of colorfulness and the colorfulness attribute result from perceptual experiments. It is obvious that the higher estimated value stands for more colorful of the test image.

Blind image quality assessment for HDRI: Section I introduced some previous evaluation works; most of them are estimate quality of virtual HDRI using HDR displays. However, the HDR displays are might available to all in the future but still too expansive now. Therefore, an iTMO evaluation

TABLE I
CORRESPONDENCE BETWEEN THE COLORFULNESS METRIC AND THE COLORRFULNESS ATTRIBUTES.

Attribute	M_{col}
not colorful	0
slightly colorful	15
moderately colorful	33
averagely colorful	45
quite colorful	59
highly colorful	82
extremely colorful	109

work without required high dynamic range display equipment is introduced in this thesis.

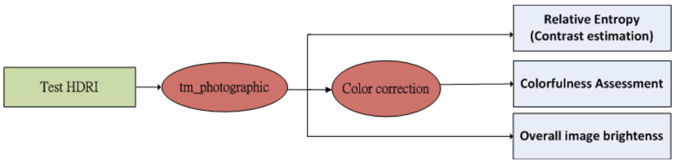

Fig. 2. The evaluation framework of image quality assessments for HDRIs

Fig. 2 shows the evaluation framework of blind image quality assessment for HDRI. In the first step, both reference HDRI and test HDRI are compressed to low dynamic range using photographic tone operator. And then a solution of color correction is applied to the compressed LDRIs. Finally there are three image attributes are estimated using methods in the following context.

There are some parameters of inverse tone mapping curves introduced in Section III need to be setting by users. One important variable is the maximum luminance after expansion to high dynamic range, which denoted as L_{wMax}. To evaluate image attributes of virtual HDRIs by using those three previously introduced NRQA metrics will encounter a problem. When a high L_{wMax} value will derive higher the image quality assessment result , but it unreasonable because we know that over stretch the contrast will introduced the noise, Moreover, higher dynamic range does not mean that higher quality when produce virtual HDRIs

The photographic tone operator: Photographic tone mapping operator is a good choice for compress the dynamic range because it can keep more fidelity than other TMOs and well verified from some inverse tone mapping evaluation work.

Reinhard at el.'s photographic tone mapping operator [30] is simple and fast, which is a combination of global luminance mapping and local dodging and burning operators. In this section, we adopted only the global part for simplification.

First step of global photographic operator is scale high dynamic luminance to mid-tone region using eq. (6):

$$L(x,y) = \frac{a}{\bar{L_w}} L_w(x,y) \tag{6}$$

Where a is setting to 0.18 for most test images, and is log-average to estimated the key value of whole image by eq. (1).

Following step is the mapping from high dynamic range to low dynamic shows in eq. (7):

$$L_d(x,y) = \frac{L(x,y)(1+\frac{L(x,y)}{L_{white}^2})}{1+L(x,y)} \tag{7}$$

Where L_{white} is defined as the maximum luminance of $L(x,y)$, this mapping curve preserves details of HDRI to the reproduced LDRI.

Color correction: Most tone mapping algorithm compress the luminance while ignore the color correction problem after the tone adjustment. A tradition tone mapping method in color channels is hold the color to luminance ratio shows in eq. (8), where C_{in} might be one color channels such as red, green or blue generally. Lout denotes compress luminance L_{in} stands for input high dynamic range luminance.

$$C_{out} = \frac{C_{in}}{L_{in}} \cdot L_{out} \tag{8}$$

Matinuk *at el.*[33] introduced two formulas to apply gamma correction of color channels after luminance tone mapping operation. The first formula is a nonlinear function extend from eq. (8) shows in eq. (9), the result luminance would be altered when s (the gamma adjustment parameter) is not equal to 1, which might cause undesirable distortion. Another formula shows in eq.(10), which is linear interpolation function that will preserve luminance, when s equal to 1, there are same result color value of eq. (9) and eq. (10). However, eq. (10) would cause hue shift from the experiment result. The choice of hue-preserving or luminance-preserving depend on the application.

$$C_{out} = (\frac{C_{in}}{L_{in}})^s \cdot L_{out} \tag{9}$$

$$C_{out} = ((\frac{C_{in}}{L_{in}} - 1) \cdot s + 1) \cdot L_{out} \tag{10}$$

Matinuk introduced an approximated model of color correction in HDR tone mapping algorithms to find out the suitable s value. The contrast factor c is denote the degree of compression level by TMO curve depicted as eq.(11) , where maximum value of Lin is scale to 1 by factor b.

$$L_{out} = (L_{in} \cdot b)^c \tag{11}$$

For more complicated TMO, the contrast factor c can be estimated by eq.(12), where = log10(L):

$$\begin{cases} L'_{out} = TMO(L'_{in}) \\ c(L_{in}) = \frac{d}{dL} TMO(L'_{in}) \end{cases} \tag{12}$$

$s(c)$ is the relation between c and s, which can be approximated with eq. (13).

Where k_1 and k_2 is obtain from curve fitting to the experiment result. Matinuk concluded both parameters for hue-preserving case and luminance-preserving case as also show in eq. (13).

$$\begin{cases} s(c) = \frac{(1+k_1)\cdot c^{k_2}}{1+k_1\cdot c^{k_2}} \\ k_1 = 1.6774, k_2 = 0.9925 \quad for \quad eq.(31) \\ k_1 = 2.3892, k_2 = 0.8552 \quad for \quad eq.(32) \end{cases} \tag{13}$$

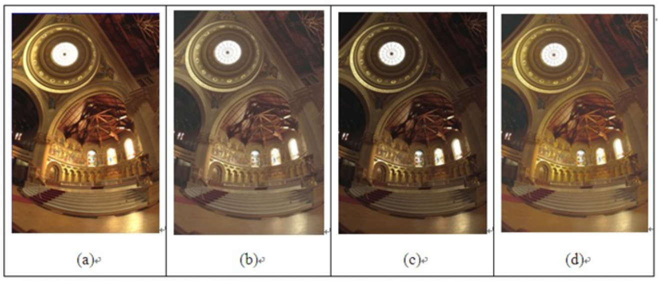

Fig. 3. (a) Original memorial church photograph with 1/shutter speed =0.25, f/stop=8. Virtual HDRI which using iS iTMO with EV=2,P=1.6 (b) A photographic tone mapping and color channels is applied using eq.(5) (c) A photographic tone mapping and color channels is applied using eq.(6) and eq.(10) (d) A photographic tone mapping and color channels is applied using eq.(7) and eq.(10)

Fig. 3 shows the result of color correction with or without using Matinuk's method. Original memorial church photograph with 1/shutter speed =0.25, f/stop=8 is from the website[24] shows in Fig. 3 (a). An virtual HDRI which using iS iTMO with EV=2, P=1.6 is used as test image. Fig. 3 (b) to (d) shows photographic tone mapping and color channels compression applying different equation. In this paper, we adopt luminance-preserving formula because of experiment results shows that color of the image shown in Fig. 3 (d) is more similar to original memorial church photograph than other images.

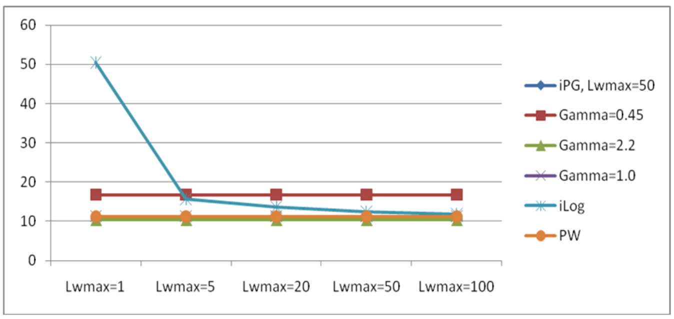

Fig. 4. Colorfulness of different L_{wMax} for iTMOs

Experiment results and discussion: There are various experiment results of image quality assessment show in this subsection. Fig. 4 to Fig. 6 show the image quality assessment results of different L_{wMax} value for iTMOs. It is obvious that the different L_{wMax} value derive the same image attributes

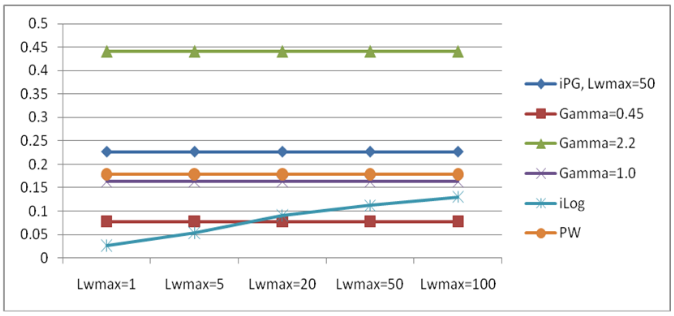

Fig. 5. RE/N of different L_{wMax} for iTMOs

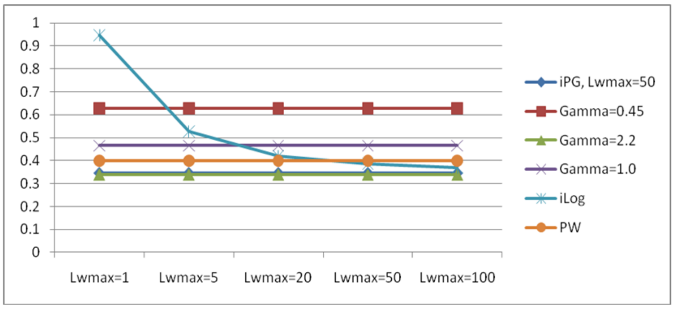

Fig. 6. Log average of different L_{wMax} for iTMO

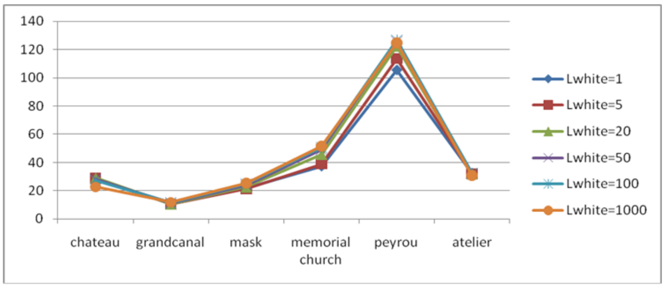

Fig. 7. colorfulness of different L_{white} for iPG

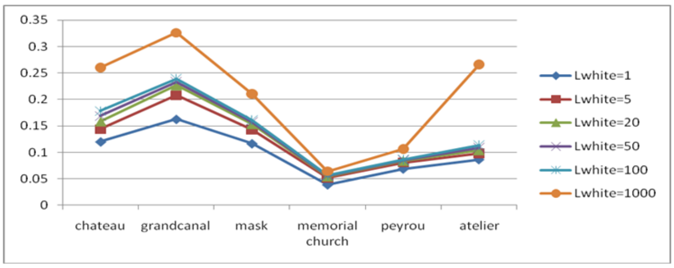

Fig. 8. RE/N of different L_{white} for iPG

except iLog iTMO. When L_{wMax} is higher enough, larger L_{wMax} doesn't affect image quality very much.

Fig. 7 to Fig. 9 show the results of different L_{white} for iPG iTMO. (L_{wMax} =100), it can be concluded that the colorfulness is not affected by different L_{white} value, however, consider the RE/N, it is quite obvious that there are higher RE/N, which mean higher contrast when L_{white} =1000. Fig.

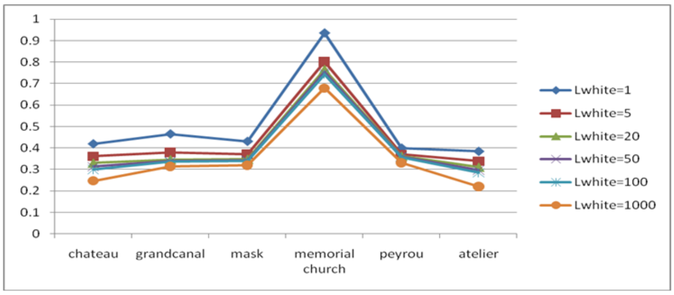

Fig. 9. Log average of different L_{white} for iPG

9 shows the overall brightness of images of different L_{white}, higher the L_{white} value will produce dark virtual HDRI.

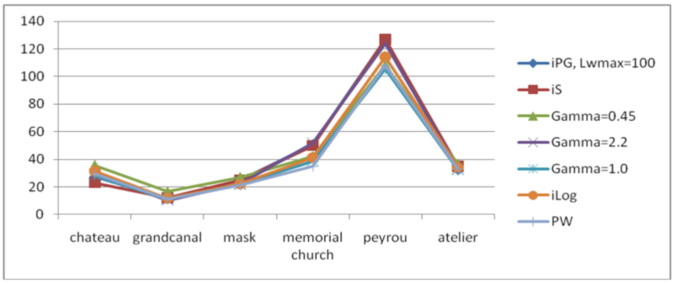

Fig. 10. Colorfulness of different iTMOs

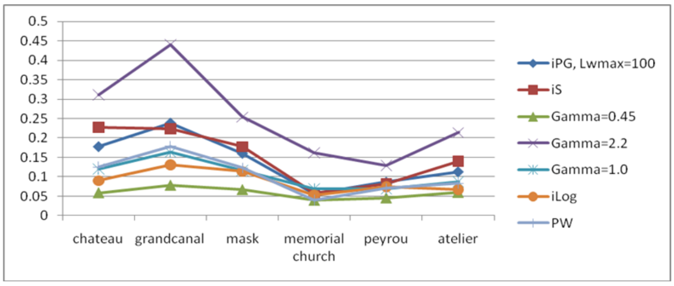

Fig. 11. RE/N of different iTMOs

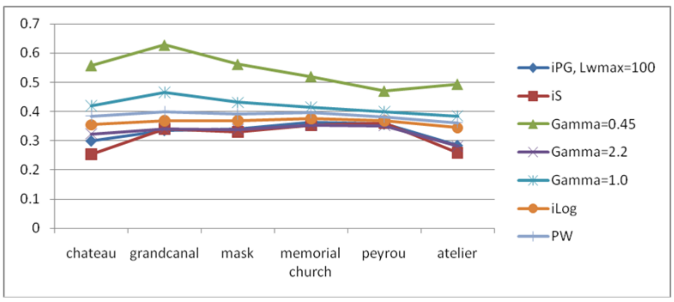

Fig. 12. Log average of different iTMOs

Fig. 10 to Fig. 12 illustrate the image quality assessment comparison of different iTMOs. The parameter settings are the same as those in Table I. It is obvious that the differences between iTMOs are very close for colorfulness. The RE/N results of various iTMOs shown in Fig. 11 conclude contrast enhancement of Gamma=2.2, iS, and iPG iTMOs have more than other iTMOs, this is agreed with our discussion of JND based contrast evaluation. Gamma=0.45 are the brighter than other iTMOs, which is also can be derived from the iTMO mapping curve.

TABLE II
AVERAGE SCORES OF PERCEPTUAL EXPERIMENTS .

	Part1	Part2
iPG	4.30	4.49
iS	4.07	4.59
Gamma(0.45)	2.79	2.73
Gamma(2.2)	3.71	4.34
Gamma(1.0)	4.43	4.17
iLog	2.90	3.43
PW	3.97	3.87

Perceptual experiment: We design a perceptual experiment to test the image quality of those iTMO images, and try to conclude an overall image quality matrix from those image attributes. There are 16 subjects within the ages 22 to 36 in this experiment. We asked subjects to rate the results of iTMOs, those virtual HDRIs are compressed to low dynamic range domain by photographic tone mapping because the limitation of LCD display used for this experiment.

There are total 42 images within 6 test scenes shows in Fig. 10. For each scene, there are 7 virtual HDRIs from different iTMOs introduced in section III are applied tone mapping to LDRIs.

Those LDRIs from virtual HDRIs are shown on screen randomly. This experiment is composed of two parts. In the first part, we asked subjects to rate every test image independently, there are no more than two images are shown on screen at the same time. For each image, a range of integers from 0 to 7 are possible choice as an overall image quality score. In the second part, we prepared an original input LDRI as the reference image, asked subjects to observe the difference between original LDRI and LDRIs from virtual HDRIs, and then make a decision for image quality scores.

Table II is the average scores of the first part of proposed perceptual experiment (no reference LDRI), the virtual HDRIs from iPG, Gamma=1.0, Gamma=2.2 and iS iTMOs have relative better results than other iTMOs. When subjects referred original LDRI when rating scores, it is obvious that result of iS iTMO obtain higher score than that of the first part of proposed experiment, which also depicted in table II .

IV. CONCLUSION AND FUTURE WORK

Conclusion: This paper presents blind Image quality assessments which estimate image attribute of virtual HDRIs such as contrast, brightness, and colorfulness without information of reference images. The analysis of contrast and brightness match with the shapes of iTMO curves.

V. Conclusion

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