# RENDERING HIGH DYNAMIC RANGE IMAGES

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## ABSTRACT

**A high dynamic range (HDR) imaging system, KIM05, has been developed to overcome the limitations of dynamic range of a typical digital image reproduction system. The first stage is an HDR image-assembling algorithm, which constructs an HDR image from a sequence of multiple image exposures of a scene. The second stage utilises a new file format to store the HDR image in three primaries of 16-bits each. The third stage, described in this paper, uses a new tone-mapping algorithm to display HDR images on typical displays, optimised for sRGB devices. Six HDR tone-mapping techniques were evaluated by observers, and the new technique showed the best performance in all four category judgements: overall, tone, colour, and sharpness.**

## 1. BACKGROUND

Real-world scenes have a much wider range of luminance than typical digital imaging systems are able to represent. The range of luminance of a sunny day, from the brightest points in direct sunlight to the darkest shadows in overcast conditions, may be up to nine or ten orders of magnitude, whereas the range of a typical digital imaging device is only three orders of magnitude. A graphic image file with 8-bits signal depth in each channel has a dynamic range of 255:1, corresponding to a maximum density of 2.4. This range is appropriate for standard output devices, for example CRT display and offset print, which may have a dynamic range of only 100:1, (density 2.0).

**Figure 1.** It is almost impossible with conventional film photography to capture both the highlight details in the bride's dress and the shadow details in the church interior in a single exposure.

When a photographer tries to capture a scene that has areas of both low and high illumination, he will have a problem in capturing all tonality of the scene simultaneously. A classic example is a wedding photograph of the bride and bridegroom standing at the church door on a sunny day with the dimly lit interior of the church in the background (Figure 1). Unless he has a very wide latitude film, the photographer in such a case must compromise, by setting an exposure appropriate for a given luminance range. The inevitable result is that, when capturing a scene having a large dynamic range exceeding that of the camera, detail will be lost in either the highlights (over-exposed) or the shadows (under-exposed) or both. One solution to this problem in conventional photography is the 'bracketing' of exposures, by taking a series of images at fixed aperture (*f*-stop) at different exposure durations.

## 2. PREVIOUS HDR IMAGE RESEARCH

Because an HDR image contains a much larger dynamic range of radiance levels than those of a typical display, it must be mapped by a compressive transform into the display colour space. Tone reproduction is generally more important than colour information for image quality. Tumblin and Rushmeier [1] introduced the concept of tone reproduction to the computer graphics community. They developed a tone reproduction operator that preserves brightness relationships, by using a psychophysical model of brightness perception. Scene luminances were mapped to display luminances such that the perceived brightness of a region on the display would match the perceived brightness of a region in the scene. In the *Radiance* lighting simulation and rendering system, Larson *et al.* [2] mapped the original image to the output range, while attempting to preserve the subjective perception of the scene by a mixture of tone reproduction and histogram equalisation methods. The model also accounts for glare, acuity, and colour sensitivity, and thus simulates human visual perception.

Pattanaik *et al.* [3] developed a very elaborate computational model of visual adaptation for realistic image synthesis, which focused on the simulation of cone and rod responses at varying illumination levels. DiCarlo and Wandell [4] tried to combine Larson's histogram equalisation method and spatial varying contrast adaptation. They followed the Gaussian spatial operator model with multi-resolution processing, and introduced a new weighting function to reduce halo effects. Reinhard *et al.* [5] were inspired by the spatial appearance model and the photographic zone system developed by Ansel Adams. The darkroom 'burn' function reduces the lightness value in areas of high illumination, whereas the 'dodge' function raises the lightness value in dark areas. Durand and Dorsey [6] introduced a fast bilateral edge-preserving filter, which compresses contrast while preserving the details of the original image.

Johnson and Fairchild [7] introduced a new image appearance model, iCAM, which combined a traditional colour appearance model and a spatial vision model. They showed how iCAM could be used for HDR image rendering, but is important to stress that iCAM was not designed specifically as a tone-mapping algorithm but rather as a predictor of overall colour appearance. The Retinex technique is based on an iterative method to simulate the human visual system, and has been widely regarded as useful for compressing image contrast. Funt [8] published a Matlab implementation of Retinex theory, the Frankle-McCann model, implemented with log compression of the HDR relative radiance value. One of the most compre-hensive implementations of Retinex theory was by Meylan and Susstrunk [9], in which the HDR radiance data were compressed logarithmically then transformed into $YC_bC_r$ colour space. The Retinex iterative method was applied only to the $Y$ (luma) levels.

# 3. DISPLAY CHARACTERISATION

An Apple Cinema LCD Display, with 20-inch diagonal, was chosen as the output device for display of HDR images. The display was measured in a darkroom at 20 cm distance normal to the screen surface, using a Jeti Specbos 1200 spectroradiometer, with spectral range 380…780 nm and waveband of 9nm. The distribution of spectral radiance (Figure 2 right) shows peaks on each channel, because a fluorescent lamp is used as the backlight of the display [10]. The measured luminance levels indicated slight non-uniformity across the display screen area (Figure 2 left), with a maximum luminance of approximately 240 cd/m$^2$ and average of 225 cd/m$^2$. The maximum contrast ratio (mean white divided by mean black) of the display was 102, corresponding to a dynamic range of approximately 2.0. This makes very clear the need for tone compression to display any HDR image, which might have a dynamic range of up to five to six orders of magnitude.

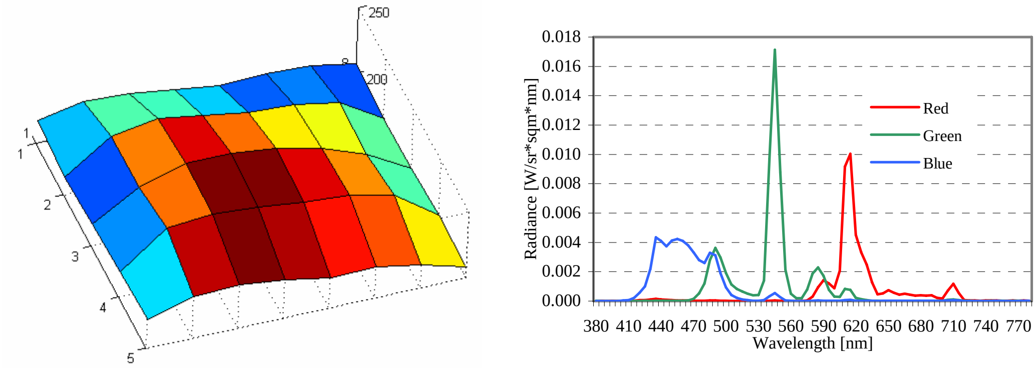



**Figure 2.** (left) Surface plot of the luminance uniformity over the display screen area; (right) Spectral radiance distributions for primaries of the Apple Cinema Display.

Typical LCD displays exhibit an electro-optic response with a sigmoidal shape, but many LCD manufacturers already build correction tables into the display video card. The resultant LCD response mimics the gamma function response of a CRT, because the typical consumer colour image file is based on a gamma-corrected colour space. The measured display also shows a response similar to a gamma function (Figure 3 left). The slope of the best-fitting line on log-log axes was approximately 2.41 (Figure 3 right), from which it is evident that there remains some sigmoidal shape to the curve, so that a simple gamma function cannot fit the response perfectly.

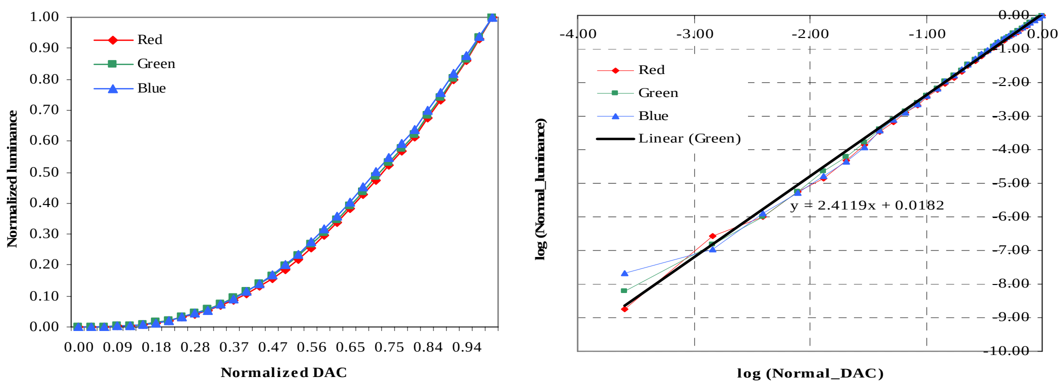



**Figure 3.** Opto-electronic transfer functions of the RGB channels of the Apple cinema LCD display: (left) on linear axes; (right) on logarithmic axes.

# 4. DEVELOPMENT OF TONE MAPPING ALGORITHM

An assembled HDR image contains larger signal depth than the typical 8-bit signal depth of a display. In order to use this digital image data, it has first to be converted into integer values. The easiest approach would be linear scaling of the HDR image data, but because of its much larger dynamic range the image would appear much darker. In theory it might be rendered by gamma correction, assuming an sRGB display, because the HDR image has a linear relationship to scene radiance, but it still looks dark. See the samples in Figure 4.

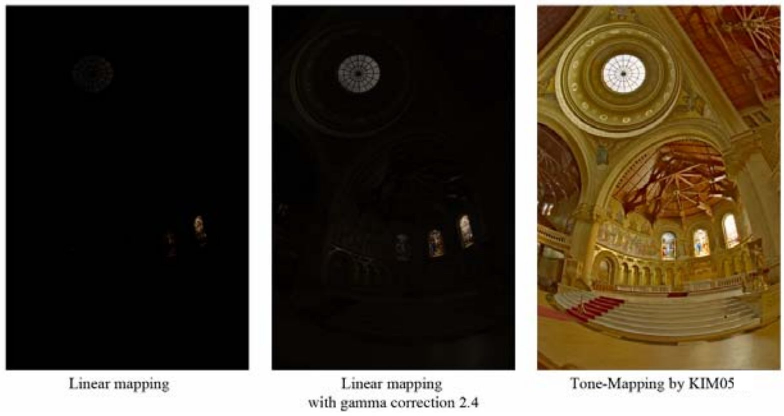



**Figure 4.** Example of simple approaches for HDR rendering and results of tone mapping: (left) Linear mapping into display DAC signal; (centre) Linear mapping through gamma 2.4 correction; (right) HDR rendering by tone mapping algorithm. The image sample was downloaded from Debevec's website (www.debevec.org).

## 4.1 Global adaptation

The HDR primaries contain relative levels of scene radiance. However, the dynamic range of the image is much larger than that of the display, so the radiance distribution of an image must be compressed. The two most popular approaches are gamma compression, by power function of gamma (Eq. 1), and log compression (Eq. 2).

$$g(x,y) = f(x,y)^{1/\gamma} \qquad \text{(Eq. 1)}$$

$$g(x,y) = \log[\alpha + f(x,y)] \qquad \text{(Eq. 2)}$$

where: *f(x,y)* is pixel value.

The log function is a very effective choice for HDR tone mapping in terms of mathematics, because it can compress a large range of data, and it approximates the human visual system response given by *Fechner's Law*. This method has been used by most tone mapping researchers [2, 5, 11].

After performing the gamma function, the KIM05 algorithm largely controls the variables by exponents in power functions. The tone-mapping method is mainly controlled by the exponent (hereinafter called *Gamma*) of a monotonic tone reproduction curve, which is lossless in terms of tonal information. The log compressed HDR primaries are rescaled relative to pixel levels within an image. The hypothesis is that the gamma function of the response of the human eye exceeds unity (dark contrast) in overall bright luminance conditions, and is less than unity (bright contrast) in overall dark luminance conditions on the logarithmic scale of luminance.

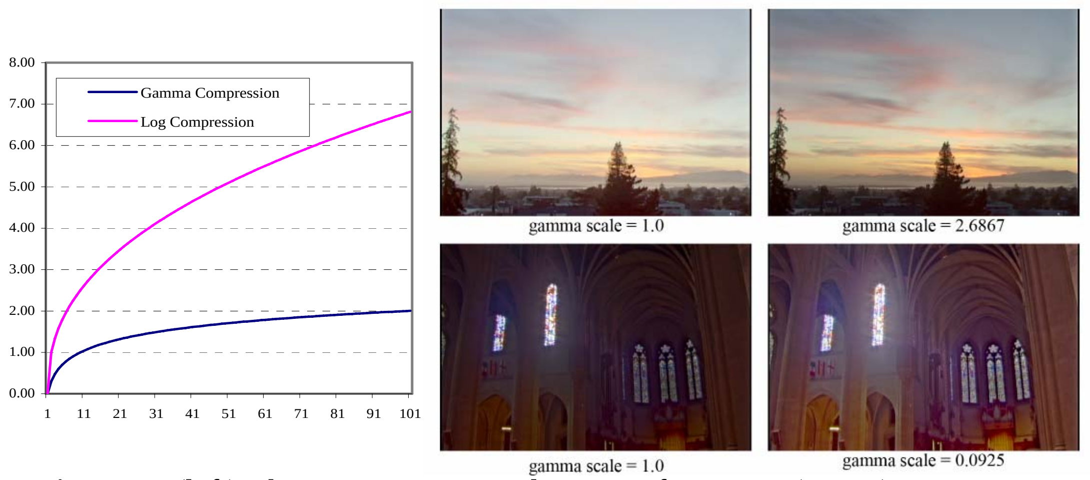



**Figure 5.** (left) Characteristic Log and Gamma functions; (centre) Image without global gamma scaling; (right) Image with gamma scaling by arithmetic mean. The image sample was downloaded from Debevec's website.

An arithmetic mean was computed from the log-compressed pixel levels:

$$g(x,y)=\left\{\log[\alpha+f(x,y)]\right\}^{k\cdot\gamma} \qquad \text{(Eq. 3)}$$

where: *f(x,y)* are the HDR primaries; *k* is the log-compressed image gamma; and $\gamma$ is the scaling constant for global gamma.

### 4.2 Local Luminance Adaptation

This method has been used by many researchers. Pattanaik *et al.* [3] used a pyramid Gaussian filter; DiCarlo [4] used multi-resolution robust Gaussian filter; Reinhard *et al.* [5], Johnson and Fairchild [7], and Meylan and Susstrunk [9] used Discrete Fourier Transformation filter to reduce artefacts of the Gaussian filter.

**Figure 6.** (left) Result of log-compression without local luminance adaptation; (right) Result of HDR imaging algorithm, KIM05 from assembling to tone-mapping

Figure 6 (left) shows a typical example of log-compression, which cannot manage the tone reproduction in terms of contrast. The shadows are too dark to show the details. Local luminance adaptation is required as a subsequent stage, which may work in a similar way as a sub-light in photographic lighting technique. For luminance adaptation, the luminance component was a weighted sum of the three colour channels:

## 4.3 Display Device Adaptation

The luminance profile contributes significantly to the adjustment of the luminance level. However, the colourfulness of the image overall decreases as a result, and the overall contrast is reduced. The display device adjustment should ideally follow the stages of gamut mapping, clipping, sigmoidal tone compression (for LCD), and chroma enhancement. The target colour space in KIM05was standard sRGB, which has gamma 2.4 in tone reproduction, D65 white point and primary chromaticities of the CCIR 709 phosphor set.

**Figure 7.** Results of KIM05 imaging algorithms, from assembly to rendering.

# 5. EVALUATION OF TONE-MAPPING ALGORITHMS

In order to evaluate the HDR image rendering system, psychophysical experimental methods were used. The typical experiments for evaluation of reproduction are pair comparison and category judgement. The pair comparison method is based on *Thurstone's Law of Comparative Judgement (Case V)*, which assumes that two stimuli have the same standard deviation and no correlation. The scale is calculated from the standardised *z*-score value, assuming the human response follows a normal distribution. The category judgement method is an extension of the pair comparison method, based on *Torgerson's Law of Categorical Judgement (Condition D)* [12], where the analysed data is compared with an estimated category boundary.

The KIM05 tone-mapping algorithm was evaluated with other tone mapping algorithms. In the case of the HDR rendering, their performance was more varied than for typical gamut mapping algorithms. Thus, the category judgement method may be suitable for the evaluation of tone mapping algorithms. All the experimental data were calculated by *Torgerson's Law of Categorical Judgement* with *Category Boundary* on standardised data. In order to obtain the *z*-score, the *Logical parameter estimation method* and *Gaussian estimation method* were used.

## 5.1 Image Properties

Observers were asked their preference of the image in terms of four image properties:

(1) *Overall quality*
Which one appears to be the more pleasing image?

(2) *Tone*
Which one appears to have a rich tonality, meaning good shadow detail, good highlight detail, and overall contrast?

(3) *Colour*
Which one appears to be more natural and pleasing in colour?

(4) *Sharpness*
Which one appears to be the sharper image?

## 5.2 Viewing environment

In this experiment, the images were shown only on the Apple Cinema LCD Display, for which the maximum luminance was 247.4 cd/m$^2$. The ANSI contrast ratio was 1:102 and the dynamic range was 2.01 (log10 based). The resolution was 1680×1050 and diagonal size of the screen was 20-inch. This display was calibrated to fit the standard sRGB viewing condition. The display gamma was characterised at 2.4. White point was fixed at D65. The displayed images were inverted into characterised colour space, as described in Section 3.2.

## 5.3 Experimental Software

Software was developed in Matlab v7 for the category judgement experimentation by using GUI objects. In order to maintain the same viewing angle between landscape and portrait format, the area displaying an image was restricted to 800×800 pixels (20.5×20.5 cm). The distance of the observer was 55~60 cm from eye to display. The viewing angle was thus fixed at approximately 21.36°. All the images were presented against an 18% grey background in a dark surround. The measured luminance level of the image background was 163.8 cd/m$^2$. Reproductions of the fourteen images were displayed for each of the six different tone-mapping algorithms. The order was randomised and different for each observer. The experiment was divided into four sections, each showing 84 images, with a total of 336 judgements. The observer had to select a category by clicking a value on a nine-point scale. On average, observers finished all four sections in 40 minutes.

All tone-mapping software was downloaded from the authors' web sites, although the implementations cannot guarantee the performance of their algorithms. For convenience, each algorithm was given the primary author's surname:

(1) ***L*** – Larson's Photosphere for OS X [2]
– histogram equalization method with local luminance adaptation

(2) ***J*** – HDR Matlab implementation of iCAM [7]
– image appearance model with spatial adaptation through Fourier Transform filter.

(3) ***R*** – Reinhard's plug-in software for Debevec's HDRshop [5]
– photographic tone reproduction model with application of a photographic zone system and spatial appearance model.

(4) ***D*** – Debevec's HDRview of version 1.2 [11]
– HDR viewing program. His software did not reveal its algorithm. However, he recommended a squared logarithmic compression for displaying HDR image.

(5) ***M*** – Funt's code for McCann's Retinex in Matlab [8]
– McCann's Retinex algorithm was applied on 10-based logarithm of HDRi.

(6) ***K*** – A Matlab GUI application of KIM05 version 7.1
– logarithm-based spatial luminance adaptation model

## 5.4 Method

The HDR rendering reproductions showed a large variance (Figure 8). In order to cover this variance, nine category labels were chosen. The observer was shown the result of one of the algorithms and asked how pleasant it was on an integer scale of one-to-nine, based on the instruction in Bartleson's experiments [13]. Twenty colour-normal observers took part in the experiment. The ages ranged from twenties to fifties. Fifteen of the observers had had experience related to photography or printing engineering. Five observers were inexperienced in terms of graphic art. Eight observers were female; twelve were male. All judgements were decided in terms of pleasantness, so the results of this performance test were not related to accuracy. In general the judgements were based on subjective memory of the observers and relative imaging performance among the algorithms.

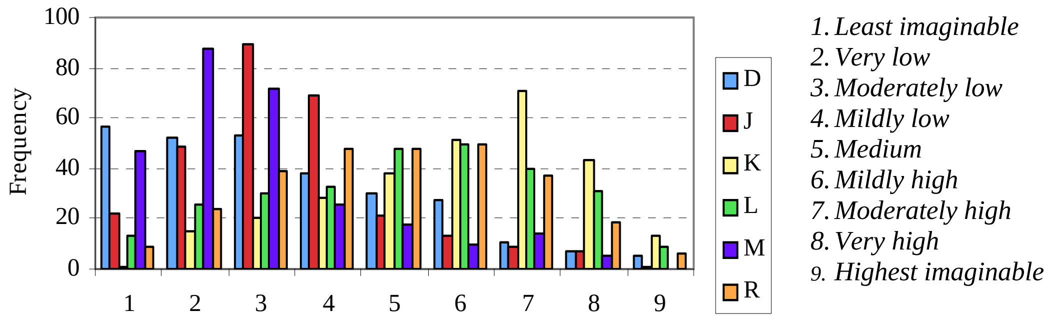
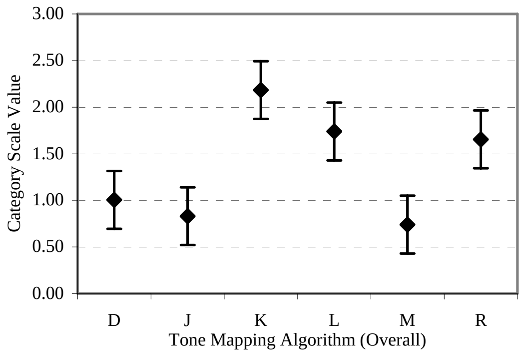



**Figure 8.** Frequency matrix of the overall judgements.

### 5.5 Results

***K*** had the best results in averaged interval scores in all judgements (Figure 9). Second, ***L*** and ***R*** had similar results, with ***L***'s result more advanced than ***R***. The performance results can be divided into two groups: first ***K***, ***L***, ***R,*** and second ***D***, ***J***, ***M***. The result for ***J*** was worst in colour judgement, because this implementation was made by default parameters without specific characterisation for iCAM. We cannot guarantee this result, because it needed its own inherent characterisation of a specific colour space. However, according to another psychophysical experiment carried out by the same institute, ***J*** was ranked as the third performer behind ***R***.



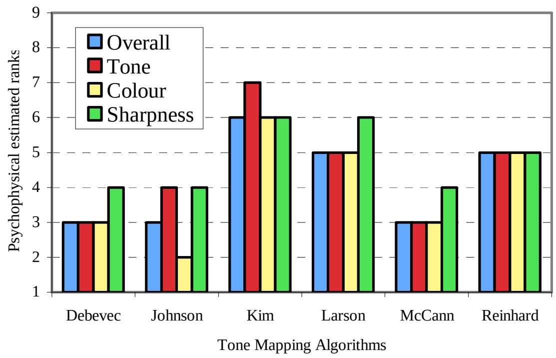




**Figure 9.** (left) Averaged interval scores of Tone-Mapping by overall judgement: (right) Psychophysical estimated rank of performance test in terms of pleasantness on overall, tone, colour, and sharpness.

In algorithms ***K*** and ***L***, the performance of colour became relatively lower than that of tone, hence ***K***'s reproduction showed that highlight colours looked faint in colourfulness. In contrast, the ***L***'s reproduction demonstrated that highlight colours appeared more saturated than the observers expected. ***R*** showed similar performance in terms of tone and colour.

## 6. DISCUSSION AND CONCLUSION

HDR imaging extends the limits of typical graphic imaging devices. This study started from how to record a scene using multiple-exposure sequences on the basis of the scene radiometry. The dynamic range variations between HDR images and a typical imaging system are much greater than those between transparency film and output devices. Tone-mapping methods are attempts to deal with this problem. Many researchers believe that we have to simulate the responses of the human eye to render HDR images well. However, they have overlooked an important point, namely that HDR primary levels are inherently relative, not absolute, in radiance levels.

All the HDR assembly processes follow a typical regression method for building an HDR image. When the regression method recovers an exposure function, it merely takes the normal exposure point as a foundation in terms of relative scaling of radiance. If the absolute radiance were not recorded as a reference, simulation the human visual system would be applicable. No-one can know whether the lowest level in an HDR image should be in the range of photopic or scotopic vision. Therefore, the rendering of HDR images should be thought of in a different way – even though the algorithm might start from simulation of human vision, it cannot be only a simulation.

The overall performance of KIM05 was found to be good. The new tone-mapping method in KIM05 showed the best performance in the HDR rendering test, followed by Larson's Photosphere and Reinhard's Photographic Tone Reproduction methods. Strictly speaking, iCAM and McCann's Retinex are not tone-mapping algorithms, and so may not be relevant for performance testing of HDR tone-mapping algorithms. The fatal problem of Retinex is the computational cost, because Retinex theory is inherently based on an iterative method.

The shortcoming of the psychophysical experiment in this project was that the differences in performance between the algorithms were large. In a future experiment, the pair-comparison method might be more appropriate than category judgement, because with more refined algorithms the differences in performance might not be so different. Further studies are required to improve the performance of the HDR algorithm. The tone-mapping algorithm can be better comprehended in terms of the general problem of colour gamut mapping. The performance of HDR tone mapping in terms of pleasantness and accuracy can be further assessed using the techniques of colour gamut mapping evaluation.

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## APPENDIX – HDR images for the psychophysical experiments

In the array of test images below, the three top images were downloaded from Debevec's website (http://www.debevec.org). The middle eight images were downloaded from the RIT/MCSL image database (http://www.cis.rit.edu/mcsl/). The bottom three images were made by the author. During implementation, all the images were built using default parameters of software. The following images were rendered by the KIM05 algorithm, version 7.1.

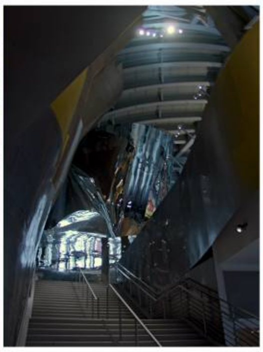

DEB11


DEB12


DEB13


LAR11


LAR12


LAR13


LAR14


LAR21


LAR22


LAR23


LAR24


KIM11


KIM12


KIM13