Perceptual Evaluation of Tone Mapping Operators with Real-World Scenes

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ABSTRACT

A number of successful tone mapping operators for contrast compression have been proposed due to the need to visualize high dynamic range (HDR) images on low dynamic range devices. They were inspired by fields as diverse as image processing, photographic practice, and modeling of the human visual systems (HVS). The variety of approaches calls for a systematic perceptual evaluation of their performance.

We conduct a psychophysical experiment based on a direct comparison between the appearance of real-world scenes and HDR images of these scenes displayed on a low dynamic range monitor. In our experiment, HDR images are tone mapped by seven existing tone mapping operators. The primary interest of this psychophysical experiment is to assess the differences in how tone mapped images are perceived by human observers and to find out which attributes of image appearance account for these differences when tone mapped images are compared directly with their corresponding real-world scenes rather than with each other. The human subjects rate image naturalness, overall contrast, overall brightness, and detail reproduction in dark and bright image regions with respect to the corresponding real-world scene.

The results indicate substantial differences in perception of images produced by individual tone mapping operators. We observe a clear distinction between global and local operators in favor of the latter, and we classify the tone mapping operators according to naturalness and appearance attributes.

Keywords: high dynamic range (HDR) images, human visual systems (HVS), tone mapping, psychophysics, ANOVA, correlation, MANOVA, Mahalanobis distances.

1. INTRODUCTION

The need of high dynamic range (HDR) images, containing broader dynamic range than most of today's display devices, has highly increased. They are useful not only for static images but also for multimedia applications. Therefore, how to produce visually compelling HDR images has been one of the important discussions in computer graphics, and a number of techniques have been introduced. To represent HDR images on low dynamic range devices, a number of successful tone mapping operators have been presented. They are useful not only for HDR photography but also for lighting simulation in realistic rendering and global illumination techniques which provide real-world luminance ranges.

Because a variety of tone mapping operators have been proposed, only a systematic perceptual evaluation can reveal the strengths and weaknesses of the wide range of approaches presented in recent years. We conducted a psychophysical experiment of a direct comparison between the appearance of real-world scenes and tone mapped images of these scenes. The primary interest of this experiment is to investigate the differences in perception of tone mapped images when they are directly compared with their corresponding real-world views and indirectly compared with each other. To our knowledge, this work is the first direct comparison of tone mapped images with corresponding real-world scenes.

In Section 2, the seven tone mapping operators selected for our experiment are briefly described. Section 3 gives an outline of our perceptual evaluation and Section 4 discusses the obtained results.

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2. TONE MAPPING OPERATORS

The concept of tone reproduction was first introduced by Tumblin and Rushmeier in 1993.[34] The goal of tone reproduction is to compress the dynamic range of an image to the range that can be displayed on physical devices in case that the luminance range of the images is much broader than that of physical devices. A number of tone mapping techniques have been presented, and most of them can be categorized into two groups: global and local operators. Global operators apply the same transformation to every pixel of an image while local ones adapt their scales to different areas of an image. The existing tone mapping operators are summarized in a recent review by Devlin.[8]

For our perceptual evaluation, seven commonly used tone mapping operators were selected. The global operators are the linear mapping and the methods of Pattanaik,[27] Ward,[38] and Drago.[9] The local operators are the fast bilateral filtering presented by Durand and Dorsey,[10] Ashikhmin,[2] and Reinhard[31] methods. In the following sections, we briefly discuss each of those operators.

2.1. Global Operators

The simplest tone reproduction is a linear mapping which scales the radiances to the range between 0 and 255. If the logarithm of the radiances is taken and linearly scaled to $[0, 255]$, it is called a logarithmic linear mapping.

The histogram adjustment tone mapping operator developed by Ward Larson et al.[38] builds on earlier work.[12,36] The algorithm features strong contrast compression for pixels belonging to sparsely populated regions in the image histogram, which helps to overcome the problem of dynamic range shortage. This method leads to a monotonic tone reconstruction curve which is applied globally to all pixels in the image. The slope of the curve is constrained by considering the human contrast sensitivity to guarantee that the displayed image does not exhibit more contrast than what is perceived in the real scene.

Pattanaik et al. extended the perceptual models framework by Tumblin and Rushmeier[34] and presented a new time-dependent tone mapping operator which is based on psychophysical experiments and a photoreceptor model for luminance values.[27] This algorithm deals with the changes of threshold visibility, color appearance, visual acuity, and sensitivity over time. This algorithm briefly can be decomposed into two models: the visual adaptation model and the visual appearance model. The signals that simulate the adaptation measured in the retina are used for adaptation in each pixel of an image. To reproduce visual appearance, it is assumed that a viewer determines reference white and reference black colors. Then, the visual appearance model recalculates the visual appearance values with those reference points. By assembling those visual adaptation and appearance models, the scene appearance is reproduced with changes to visual adaptation depending on time. This method is also useful to predict the visibility and appearance of scene features because it deals with reference white and black points.

Drago et al. introduced a method which is called adaptive logarithmic mapping.[9] This method addresses the need for a fast algorithm suitable for interactive applications which automatically produces realistically looking images for a wide variation of scenes exhibiting high dynamic range of luminance. This global tone mapping function is based on logarithmic compression of luminance. To preserve details while providing high contrast compression, a family of logarithmic functions ranging from $\log_2$ to $\log_{10}$ with increasing compressive power are used. The $\log_{10}$ is applied for the brightest image pixel and for remaining pixels the logarithm base is smoothly interpolated between values 2–10 as a function of their luminance. Perlin bias power function[29] is used for interpolation between the logarithm bases to provide better steepness control of the resulting tone mapping curve.

2.2. Local Operators

Reinhard et al. presented a photographic tone reproduction inspired by photographic film development and the printing process.[31] The luminance of an image is initially mapped by using a global tone mapping function to compress the range of luminance into the displayable range. To enhance the quality of an image, a local adaptation is based on photographic "dodging and burning" technique which allows a different exposure for each part of the applied image. The most recent version of this method operates automatically, freeing the user from setting parameters.[30] To automate processes, low contrast regions are found by a center-surround function at different scales. Then, a tone mapping function is locally applied. The automatic dodging and burning method enhances contrast and details in an image while preserving the overall luminance characteristics.

Ashikhmin presented a new tone mapping method which works on a multipass approach.[2] The method takes into account two basic characteristics of the human visual systems (HVS): signaling absolute brightness and local contrast. This method first calculates local adaptation luminance by calculating an average luminance of neighboring pixels fitting in a bound-limited contrast range (similar to Reinhard et al.[31]). Then, it applies the capacity function which is based on the linearly approximated threshold vs. intensity function and calculates the final pixel values. The final calculation restores the details which may be lost in the steps of compression. A tone mapped pixel value is obtained by multiplying a detail image given by the ratio of pixel luminance to the corresponding local world adaptation.

A fast bilateral filtering method was presented by Durand and Dorsey.[10] This method considers two different spatial frequency layers: a base layer and a detail layer. The base layer preserves high contrast edges and removes high-spatial frequency details of lower contrast. The detail layer is created as the difference of the original image and the base layer in logarithmic scale. After contrast compression in the base layer, both layers are summed up to create a tone mapped image.

3. PERCEPTUAL EVALUATION

Image comparison techniques can be roughly classified into two major categories: subjective and objective methods. Subjective methods obtain data from human observers and the data are usually analyzed by statistical techniques.[24,25,39] Objective methods are based on theoretical models which can be either purely image processing techniques[19,20,35,40] or models incorporating some characteristics of the human visual systems (HVS).[1,5,6,13,16,18,26] A number of surveys on image quality measurements have been presented.[3,4,11,15,22,41]

3.1. Experimental Design and Participants

We selected a human-perception based method for our experiment with seven tone mapping operators (see Section 2) because our goal is a comparison of tone mapped images and their corresponding real world views and there exists no objective method to accommodate such as a cross-media comparison.

The experiment was performed with the participation of 14 human observers. All of the 14 participants were graduate students and researchers of the Computer Graphics group in the Max-Planck-Institut für Informatik. Two of them are female and the rest are male. The range of their age is 24 – 34. All of them were naïve for the goal of the experiment and tone mapping operators. Additionally, every participant reported normal or corrected eyesight to normal vision.

3.2. Acquiring HDR Images

Figure 1 shows the acquired images for our perceptual evaluation. We selected indoor architectural scenes because the scene setup conditions are easily reproducible for an experiment. As seen in the figure, the dynamic ranges of both scenes are large enough to require HDR. Scene 1 has bright spot lights around the trees and quite dark areas behind the glass. Scene 2 also has highly bright and dark areas, and in addition, it has some gray area (on pipes) which, as pointed out by Gilchrist, result in a scaling problem.[14] The scaling problem concerns how the range of luminances in an image is mapped onto a range of perceived grays. The absolute luminances in both scenes were measured by a MINOLTA light meter LS-100.[17] In Scene 1, the brightest area is 13,630 cd/m^2 and the darkest area is 0.021 cd/m^2. In Scene 2, the brightest area is 506.2 cd/m^2 and the darkest area is 0.019 cd/m^2.

To acquire HDR images for our perceptual evaluation, a Kodak Professional DCS560 digital camera and CANON EF lenses 24mm and 14mm were used to take pictures with different shutter speeds ranging from 1/2000 to 8.0 seconds. Because those images were saved in a raw format of Kodak, they were converted to 36-bit TIFF format by using the program `raw2image` included in the Kodak DCS Photo Desk Package. To recover the camera response curve function, there exist several techniques.[7,23,32,37] We used one of the newest methods, the Robertson et al. method,[32] for static images to recover the camera response curve. The HDR images were constructed with the recovered response curve and saved in the Radiance RGBE format. Each HDR image was created using 15 static images.

(a) Scene 1. Maximum pixel luminance: 4,848.9506, minimum luminance: 0.0076, dynamic range: 638,019:1.

(b) Scene 2. Maximum pixel luminance: 159.697, minimum luminance: 0.006, dynamic range: 26,616:1.

Figure 1. View of scenes selected for our tone mapping evaluation.

3.3. Experimental Procedure

Prior to the main experiment, we conducted a pilot study with experienced subjects to fine tune the parameter settings for each tone mapping operator. From a selection from multiple tone mapped images for every tone reproduction, we asked subjects to choose the best image. Additional post-processing, such as gamma correction, was performed according to the suggestions in each respective paper of the tone mapping operators. All of the images used in our experiment are shown in Appendix A. All of the HDR images and our implementations of the tone reproductions used in the experiment are available at our website*.

In the main experiment, the participants were asked to stay in the same position as each of the HDR images had been taken (Figure 1) and view seven images one after another for each of the two scenes. An sRGB-calibrated monitor (DELL UltraSharp 1800FP) displaying images of resolution 1280×1024 at 60.0 Hz was used. The subjects were asked to compare each of the 14 images with their corresponding real-world view and give ratings for image appearance and realism. Image appearance attributes judged in our experiment are overall brightness, contrast, detail reproductions in dark regions, and detail reproductions in bright regions. The subjects rated how well each of those attributes was reproduced in tone mapped images with respect to the real world view. Additionally, the subjects were asked to rate image naturalness in terms of reproducing the overall appearance of the real world views. All of the ratings were done by moving scroll bars. The subjects were allowed to move back and forth among images for one scene (see Figure 2 for an example screenshot). The whole procedure for one participant took approximately 20 to 30 minutes.

4. RESULTS AND DISCUSSION

Our experiment is a seven (tone mapping operators) $\times$ two (scenes) within-subjects design (see Tabachnick[33] for details of the design types). This experiment has two independent variables (IVs: the tone mapping operators and the scenes) and five dependent variables (DVs: overall brightness, overall contrast, detail reproductions in dark regions, detail reproductions in bright regions, and naturalness)†. Our primary interest is whether the images produced by different tone mapping operators are perceived differently when they are compared to their corresponding real-world views. For analyzing a set of data, the Statistics Toolbox of MATLAB was used.[21] As preliminary data processing, all obtained scores were normalized over each of the attributes and each of the subjects in order to scale the standard deviations 1.0 as $x_i \rightarrow \frac{x_i - \mu_x}{\sigma_x}$ where x_i is a score and μ_x and σ_x are respectively the mean and the standard deviation over an attribute of a subject.

*http://www.mpi-sb.mpg.de/resources/tmo/

†IVs are the variables which do not depend on participants while DVs depend on participants' ratings.

Figure 2. A screenshot of HTML pages presented to the participants.

4.1. Main Effects

Because two scenes were used in the experiment, the main effect of the scenes was first tested by using analysis of variance (ANOVA) (see Tabachnick[33] for details of ANOVA). The result of the main effect of the scenes showed that the difference between two scenes is not significant and small enough to be ignored. It follows our goal to investigate the tone mapping performance for indoor architectural scenes.

The main effects of tone mapping operators were tested as shown in Figure 3. Figure 3(a) shows the main effect of the tone mapping operators for overall brightness. According to the significance values, overall brightness is the most differently perceived attribute. As seen in the figure, it is manifested that images produced by the linear, Pattanaik, Ward, and Drago methods (i.e., global methods) have substantially higher overall brightness than the others. These tone mapping operators are perceived the most differently when compared to their corresponding real-world views.

The main effect for overall contrast is shown in Figure 3(b). The linear, Pattanaik, and Ward methods have higher overall contrast than the others. Global operators have stronger contrast than local ones as shown in Figure 3(b). It corresponds to the expectations because global methods require high overall contrast to retain details in low-contrast regions.

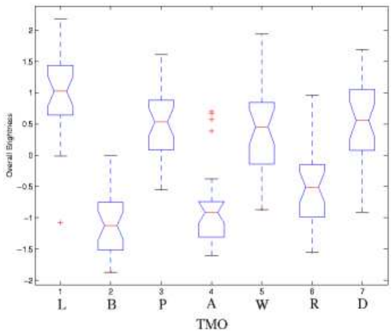
Detail reproductions in dark regions (Figure 3(c)) show the least significance among the attributes, but it is still highly significant ($p = 0.0054$). The Ashikhmin and Drago methods are perceived to have the most details reproduced in dark regions. The linear, Pattanaik, Ward, and Reinhard have almost equal scores, and the bilateral filtering has slightly more detail reproductions than those four.

Detail reproductions in bright regions is the second most differently perceived attribute as shown in Figure 3(d). The bilateral filtering, Ashikhmin, and Reinhard methods provide significantly more detail reproductions in bright regions than the others. According to Figure 3(d), all of the local operators are perceived with more detail reproductions than global ones. This result comes from the fact that local operators use different scales for small regions of an image while global operators use only one scale for the whole image and tend to saturate bright parts of an image.

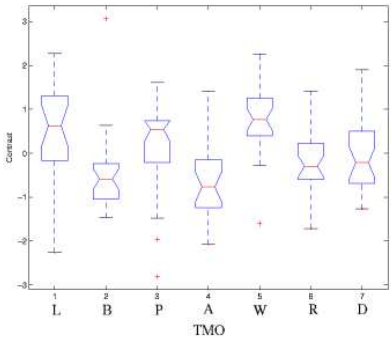
Figure 3(e) shows the main effect for naturalness. As can be seen in the figure, the Ward, Reinhard, and Drago methods are perceived with the most naturalness.

4.2. Correlations

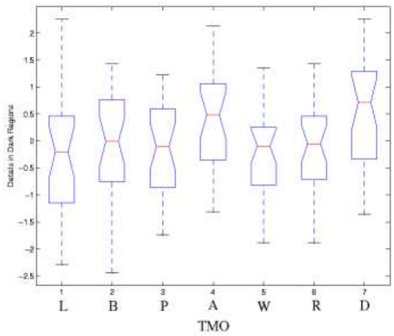
The correlations between all attributes were tested using the Pearson r correlation coefficient.[28] All of the Pearson r values between each pair of the attributes are shown in Table 1. As shown in the table, pairs of the naturalness and each of the overall brightness and detail reproductions in dark regions have very weak correlations. On the other hand, the naturalness and each of the overall contrast and detail reproductions in bright regions have stronger correlations, but they are still small. It can be concluded from this result that none of those image appearance attributes has strong influence to determine naturalness by itself.



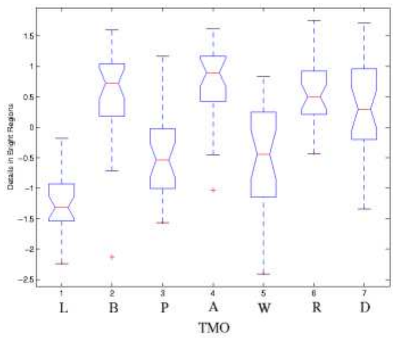
(a) Overall brightness.
$F = 46.14, p = 0.0$.



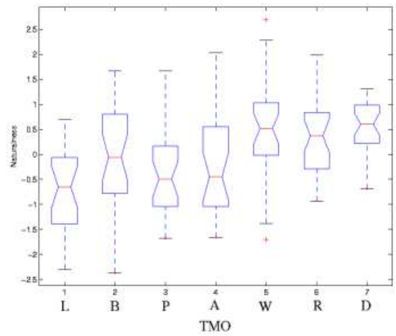
(b) Overall contrast.
$F = 8.74, p = 2.1058E - 08$.



(c) Detail reproductions in dark regions.
$F = 3.18, p = 0.0054$.



(d) Detail reproductions in bright regions.
$F = 30.355, p = 0.0$.



(e) Naturalness.
$F = 8.11, p = 8.3877E - 08$.

Figure 3. Distributions and F and p values of each attribute for the main effect of the tone mapping operators. The tone mapping operators are labeled as linear (L), bilateral filtering (B), Pattanaik (P), Ashikhmin (A), Ward (W), Reinhard (R), and Drago (D) methods. A box shows the lower quartile, median, and upper quartile values. The whiskers are lines extending from each end of the box to show the extent of the rest of the data.

	O.C.	D.D.	D.B.	N.
O.B.	0.3321	-0.1023	-0.55880	-0.0844
O.C.		-0.1114	-0.28220	0.2440
D.D.			0.26340	0.0729
D.B.				0.3028

Table 1. Correlations with the Pearson r values of all pairs of overall brightness (O.B.), overall contrast (O.C.), detail reproductions in dark regions (D.D.), detail reproductions in bright regions (D.B.), and naturalness (N.).

The pair of the overall brightness and detail reproductions in bright regions has the biggest negative correlation with the Pearson coefficient $r = -0.55880$. It is expected because as overall brightness decreases, bright parts are less saturated and better visible.

4.3. Dimension Estimate

In addition, the data were analyzed by using multivariate analysis of variance (MANOVA). MANOVA is an extension of ANOVA to analyze multiple IVs and/or multiple DVs (see Tabachnick[33] for details). MANOVA in the Statistics Toolbox of MATLAB provides an estimate of the dimension d of the space containing the group means and the significance values for each of the dimensions. If $d = 0$, it indicates that the means are at the same point. A value of $d = 1$ indicates that the means are different but along a line, value $d = 2$ shows that the means are on a plane but not along a line and similarly for higher values of d. The null hypotheses are tested by calculating the significant values (p-values) in each of the dimensions such as the means are in N-dimensional space, where N is the number of dimensions. From our set of data, MANOVA returns $d = 3$ which indicates that the means are in a space with at least three dimensions. The p values for each of the dimensions in our perceptual experiment are

$$\begin{aligned} p(d=0) &= 0.0000 \\ p(d=1) &= 0.0000 \\ p(d=2) &= 0.0017 \\ p(d=3) &= 0.9397 \\ p(d=4) &= 0.8833. \end{aligned}$$

For value $d = 3$, the possibility is the largest and above the significance level; therefore, the means are located in an at least three-dimensional space.

4.4. Mahalanobis Distances

MANOVA in MATLAB provides the Mahalanobis Distances of IVs. Mahalanobis distance is a correlation-based measure of similarity of data points relative to the probability distribution of data, which has different variances along different dimensions. Table 2 shows the Mahalanobis distances among the tone mapping operators given by MANOVA. According to Table 2, the linear tone mapping and bilateral filtering are perceived the most differently when compared with their corresponding real-world views. The second and the third most different combinations come from the combination of the linear tone mapping and Ashikhmin method and of the linear tone mapping and Reinhard method. All of the three biggest differences are provided from the linear tone mapping. On the other hand, the least difference is provided between bilateral filtering and the Ashikhmin method. This result is visualized in Figure 4 as a dendrogram plot of a hierarchical binary tree. An interesting result shown in Figure 4 is that those seven tone mapping reproductions are divided into global and local methods by Mahalanobis distances. Three local operators (bilateral, Ashikhmin, and Reinhard) are similar to each other and four global operators (linear, Pattanaik, Ward, and Drago) are similar to each other, but both categories of global and local operators are separated by a large distance.

	bilateral	Pattanaik	Ashikhmin	Ward	Reinhard	Drago
linear	**15.4530**	1.6541	**14.2361**	2.7122	**10.6089**	6.6940
bilateral		7.4749	<u>0.6674</u>	9.2726	1.3353	8.8120
Pattanaik			6.4395	<u>1.1613</u>	3.9887	2.8066
Ashikhmin				8.9709	<u>1.2405</u>	6.2989
Ward					4.5301	2.9536
Reinhard						3.7406

Table 2. Mahalanobis distances among the tone mapping operators provided by MANOVA. The three biggest distances are written in a bold font and the three smallest distances are underlined. All of the biggest differences are from the linear tone mapping. Those Mahalanobis distances are visualized in Figure 4.

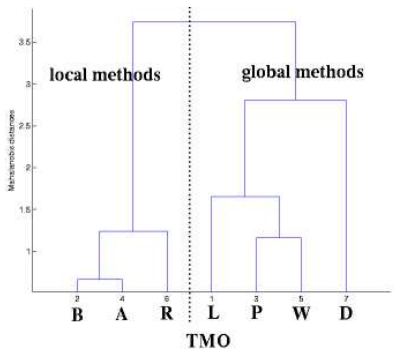


Figure 4. Tree-structured Mahalanobis distances to determine similarity among the tone mapping operators given by MANOVA. As in Figure 3, the tone mapping operators are labeled as linear (L), bilateral filtering (B), Pattanaik (P), Ashikhmin (A), Ward (W), Reinhard (R), and Drago (D) methods.
Note that those tone mapping operators are divided into global and local methods by Mahalanobis distances.

5. CONCLUSIONS

We conducted a psychophysical experiment over seven tone mapping operators and two scenes with 14 human observers. The result of the analysis shows that the seven tone mapping operators were perceived very differently in terms of all of the attributes when compared to their corresponding real-world views. Overall brightness shows the most significant differences among the tone reproductions, and global operators (the linear, Pattanaik, Ward, and Drago methods) have more brightness than local ones (the bilateral filtering, Ashikhmin, and Reinhard methods). For overall contrast, global operators have more contrast than local ones, but the difference is not as large as for overall brightness. The linear, Pattanaik, and Ward methods show more overall contrast reproduction than the others. Detail reproductions in dark regions shows the least significance value among the attributes, but it is still highly significant. The Ashikhmin and Drago methods are perceived as the most detailed one in dark regions. Detail reproduction in bright regions is the second most differently perceived attribute. In contrast to overall brightness, local operators are perceived with significantly more detail reproductions in bright regions than global ones. About naturalness, the Ward, Reinhard, and Drago methods are perceived as the most natural ones.

Correlations between naturalness and each of the image appearance attributes were tested. The result shows that none of the image appearance attributes has a strong influence on the perception of naturalness by itself. This may suggest that naturalness is dependent on a combination of the other attributes. All the other possible pairs between attributes were also tested. The biggest negative correlation happens between overall brightness and detail reproductions in bright regions which may be due to saturation or contrast compression in bright regions.

The multivariate analysis of variance (MANOVA) shows that the means of the set of data are embedded in an at least three-dimensional space. In terms of the similarity of the tone mapping operators computed by Mahalanobis distances, the biggest differences are between the linear tone mapping and each of the fast bilateral filtering, the Ashikhmin method, and the photographic tone reproduction by Reinhard et al. (i.e., local methods). The least differences are between fast bilateral filtering and the Ashikhmin method, between the methods of Pattanaik and Ward, and between the Ashikhmin method and the photographic reproduction. The Mahalanobis distances are visualized in a dendrogram plot and it shows that those tone mapping operators are divided into global and local categories in terms of similarity.

Our results demonstrate that qualitative differences in tone mapping operators have a systematic effect on the perception of scenes by human observers. They provide a solid basis for selecting the appropriate algorithm for a given application and for assessment of new approaches to tone mapping techniques.

APPENDIX A. TONE MAPPED IMAGES

Figures 5 and 6 show the tone mapped images which were used in our perceptual experiment.

(a) Linear

(b) Bilateral filtering by Durand and Dorsey

(c) Pattanaik

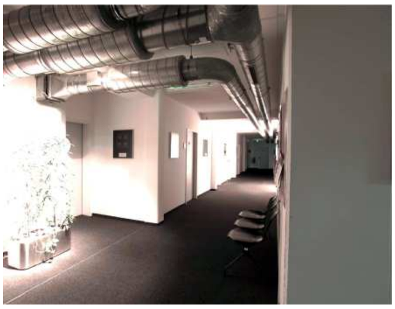
(d) Ashikhmin

(e) Ward

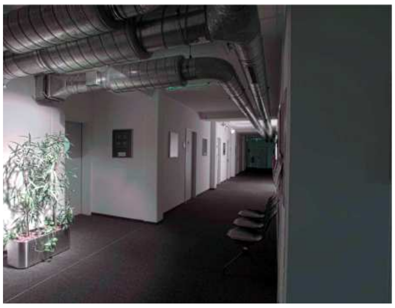
(f) Reinhard

(g) Drago

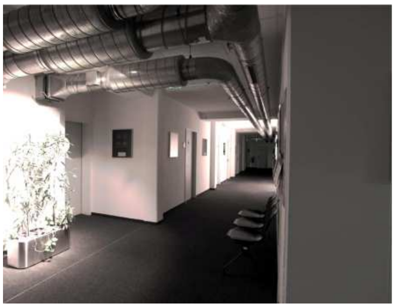
Figure 5. The tone mapped images for Scene 1.



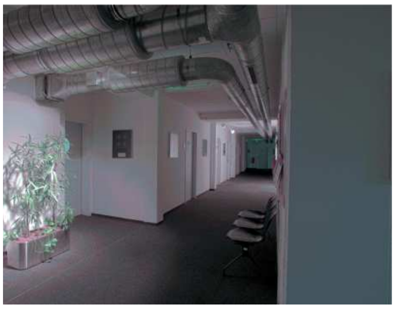
(a) Linear



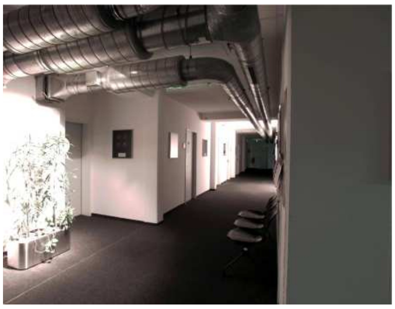
(b) Bilateral filtering by Durand and Dorsey



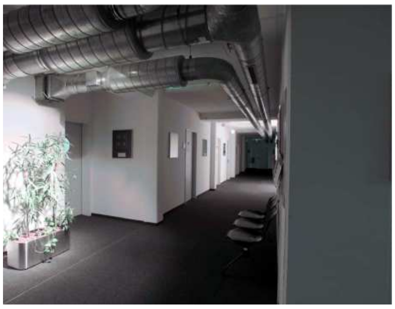
(c) Pattanaik



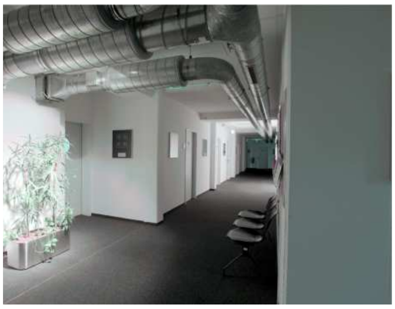
(d) Ashikhmin



(e) Ward



(f) Reinhard



(g) Drago

Figure 6. The tone mapped images for Scene 2.

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