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Image Attributes and Quality for Evaluation of Tone Mapping Operators

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Abstract

The problem of reproducing high dynamic range images on devices with restricted dynamic range has gained a lot of interest in the computer graphics community. There exist various approaches to this issue, which span several research areas including computer graphics, image processing, color science, physiology, neurology, psychology, etc. These approaches assume a thorough knowledge of both the objective and subjective attributes of an image. However, no comprehensive overview and analysis of such attributes has been published so far.

In this paper, we present an overview of image quality attributes of different tone mapping methods. Furthermore, we propose a scheme of relationships between these attributes, leading to the definition of an overall image quality measure. We present results of subjective psychophysical tests that we have performed to prove the proposed relationship scheme. We also present the evaluation of existing tone mapping methods with regard to these attributes.

Our effort is not just useful to get into the tone mapping field or when implementing a tone mapping operator, but it also sets the stage for well-founded quality comparisons between tone mapping operators. By providing good definitions of the different attributes, user-driven or fully automatic comparisons are made possible at all.

1 Introduction

The dynamic range of visual stimuli in the real world is extremely large. Several different computer technologies can produce high dynamic range luminance maps (images) of synthetic graphics or real scenes, but the conventional media used to present these images can only display a limited range of luminous intensity. This problem, i.e., displaying high contrast images on output devices with limited contrast, is the task of *high dynamic range imaging*. A number of different tone mapping methods (or operators) have been proposed in history [9, 29]. However, also due to their sheer number, the advantages and disadvantages of these methods are not immanently clear, and therefore a thorough and systematic comparison is highly desirable.

The field of tone mapping assumes extensive knowledge of findings from various scientific areas. In order to conduct a comparison of tone mapping methods, it is necessary to settle upon a set of *image attributes* by which the images produced by the methods should be judged. These attributes are not independent, and their interrelationships and the influence on the overall image quality need to be carefully analyzed. This is useful not just for comparing existing HDR approaches, but for evaluating of *future ones* as well.

In this paper, we give a comprehensive list of most of important attributes involved in the evaluation of a tone mapping operator, and we show which relationships exist between the basic attributes by means of two different subjective testing methods. The evaluation of the attributes and their relationships leads to the definition of an *overall image quality*. This metric can be used to judge how well a given tone mapping operator is able to produce naturally looking images. Furthermore, we present the most comprehensive comparison in terms of the number of tone mapping operators considered to date, including 14 different methods.

The paper is organized as follows. In Section 2, we overview the previous work on comparison of tone mapping methods. In Section 3, we introduce and describe the term "overall image quality". In Section 4, we give a survey of the most important image attributes for tone mapping, and we describe how different methods reproduce these attributes. In Section 5 we propose a new scheme of relationships between the image attributes. In Section 6 we describe the two applied experimental methods based on human observations, and finally in Section 7, we show and discuss the results of these experiments. The survey of image attributes and the relationships (Sec. 4, 5) is extended from [3] and incorporates our new findings.

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2 Previous Work

The history of evaluation of tone mapping methods is short. The following works (the only ones, to our best knowledge) were published only in the last three years. This due to the only recent increase in published tone mapping operators on the hand, and by the very high time, implementation, human, and other demands involved in such an evaluation on the other hand.

Drago et al. [10] performed a perceptual evaluation of six tone mapping operators with regard to similarity and preference. In their study, subjects were asked to rate a difference for all pairwise comparisons of a set of four HDR images tone mapped with the six tone mapping operators (24 images in total) shown on the screen. A multidimensional perceptual scaling of the subjective data from 11 observers revealed the two most salient stimulus space dimensions. The authors unfolded these dimensions as naturalness and detail and also identified the ideal preference point in the stimulus space. These findings were then used for raking the six tone mapping methods.

Kuang et al. [19, 18] tested eight tone mapping algorithms using ten HDR images. The authors implemented two paired comparison psychophysical experiments assessing the color and grayscale tone mapping performance respectively. In these tests, 30 observers were asked to choose the preferred image for each possible pair. The subjective data were then converted into an interval scale of preference and this scale was used for the evaluation. The results showed the consistency of tone mapping performance for gray scale and color images.

In 2005, Yoshida et al. [39] compared seven tone mapping methods on two architectural interior scenes. The 14 observers were asked to rate basic image attributes as well as the naturalness of the images by ratings. The results of this perceptual study exhibited differences between global and local tone mapping operators, the local ones showing a better outcome.

Recently, Ledda et al. [20] run an evaluation of six tone mapping methods by comparing to the reference scenes displayed on an HDR display. This HDR display allowed authors to involve many (23) input scenes. Subjects were presented three images at once (the reference and two tone mapped images) and had to choose the image closest to the reference. Statistical methods were used to process subjective data and the six examined methods were evaluated with respect to the overall quality and to the reproduction of features and details.

Some exciting contributions were published in the domain of the image quality measurement of ordinary LDR images. See the book by Janssen [16] for an overview on this topic. More specifically, Rogowitz et al. [30] conducted two psychophysical scaling experiments for the evaluation of image similarity. The subjective results were compared to two algorithmic image similarity metrics and analyzed using multidimensional scaling. The analysis showed that humans use many dimensions in their evaluations of image similarity, including overall color appearance, semantic information, etc.

Differently from the mentioned approaches, we adopt both a direct comparison of the tone mapped images to the real scene, and a subjective ranking of tone mapped images without a real reference. This enables us to confront the results from these two subjective experiments. Moreover, we also present a methodology for evaluating tone mapping methods using generally known image attributes. With 14 methods in total, the subjective study carried out to confirm this methodology also contains one of the most comprehensive comparison of tone mapping operators yet. We have already presented [3] preliminary ideas of this project and we conducted an initial pilot study to examine the testing setup. It was observed that the overall image quality is not determined by a single attribute, but it is rather a composition of them. Encouraged by these findings, we conducted a full experminent, the results of which, including a thorough discussion, new testing methodology etc. are presented in this paper.

3 Overall Image Quality

In this section, we motivate and describe a measure which is useful for determining the performance of a particular tone mapping operator.

The first question is whether it is really possible to find, based on human vision, an optimal or "exact" method to tone map an arbitrary HDR input image. Unfortunately, the answer seems to be no. Take for example a beach scene, where the absolute luminance is often above 50,000 lux. A captured photograph of that scene, viewed under normal room illumination (about 200 lux), can never reproduce the same amount of colorfulness, because this is a *psycho-physiological* effect that depends on the absolute luminance (vivid colors start to be perceived above 2000 lux). Therefore, a natural reproduction is only possible to a limited degree.

Another important question is the intent of the reproduction. The classical **perceptual** approach tries to simulate the human vision process and model the tone mapping operator accordingly. For example, a scene viewed at night would be represented blurred and nearly monochromatic due to scotopic vision. However, if it is important to understand the fine details or the structure of the visible lines in the result, i.e., the content of the image, the same scene would be represented with full detail, which would be called the **cognitive** approach. If the goal is only the pleasant appearance of the image, we speak about an **aesthetical** approach.

Any given tone mapping operator will realize a mixture of these three approaches, with a different weighting given to each [23].

In this paper, we concentrate on the perceptual approach only, and aim to characterize the *overall image quality* resulting from a tone mapping technique in a perceptual sense. In addition, we have chosen a number of important image attributes which are typically used to characterize tone mapped images, and study how well tone mapping operators reproduce these attributes: brightness, contrast, color and detail. The chosen attributes are mostly perceptual, but contain cognitive and aesthetics aspects as well. Beyond these attributes, which are related to color and spatial vision, there are some other important aspects and some "special effects" which can improve or modify the final appearance. Since some of the attributes are not independent (as we will explain later), we propose a scheme of relationships between them (Fig. 2). The goal of this work is to investigate the influence these attributes have on overall image quality, based on a subjective study.

4 Image attributes

In this section we briefly survey particular image attributes for tone mapping, and we list some typical tone mapping methods that attempt to reproduce them correctly.

4.1 Brightness

Brightness is a quantity that measures the subjective sensation produced by a particular luminance, i.e., the brightness is the *perceived luminance* [1]. Stevens [13] proposed an expression for the apparent brightness, but although the expression gives a convenient relationship between luminance and brightness for simple targets, the overall brightness of an image is more complex.

An operator by Tumblin and Rushmeier [34] attempts to preserve the overall impression of brightness using a mapping function that is based on the model by Stevens and Stevens. This mapping function matches the brightness of a real world luminance to the brightness of a display luminance. Recently, Krawczyk et al. [17] proposed an operator which aims for an accurate estimation of lightness in real-world scenes by means of the so-called anchoring theory of lightness perception. The method is based on an automatic decomposition of the HDR image into frameworks (consistent areas). Lightness of a framework is then estimated by the anchoring to the luminance level that is perceived as white, and finally, the global lightness is computed.

4.2 Contrast

Image contrast is defined in different ways, but it is usually related to variations in image luminance. There exist various basic formulae for computation of contrast, see the thesis by Winkler [38] for an overview. Matkovic et al. [22] proposed a complex computational global *contrast measure* called Global Contrast Factor that uses contrasts at various resolution levels in order to compute overall contrast.

Ward's [36] initial tone mapping operator focuses on the preservation of *perceived contrast*. This method transforms input luminance to output luminance using a scaling factor. The computation of the factor is based on Blackwell's [7] psychophysical contrast sensitivity model. Because Ward's operator scales image intensities by a constant, it does not change scene contrasts for display. Almost the same principle of contrast preservation is exploited also in other operators [15, 37].

Advanced local tone mapping methods (e.g., the method by Reinhard et al. [28] or by Ashikhmin [2]) are based on a multi-resolution decomposition of the image and approximate contrast in a way similar to Peli [26]. Mantiuk et al. [21] proposed recently a framework for perceptual contrast processing of HDR images. The authors define contrast as a difference between a pixel and one of its neighbors at a particular level of a Gaussian pyramid. This approach resembles the gradient-domain method by Fattal et al. [14].

4.3 Reproduction of colors

The sensation of color is an important aspect of the human visual system, and a correct reproduction of colors can increase the apparent realism of an output image. One important feature of the human visual system is the capacity to see the level of colors in a bright environment. This ability, measured as color sensitivity, is reduced in dark environments, as the light sensitive rods take over for the color-sensitive cone system. As the luminance level is raised, the cone system becomes active and colors begin to be seen. Furthermore, the human visual system has the capability of *chromatic adaptation*. Humans are able to adjust to varying colors of illumination in order to approximately preserve the appearance of object colors. See Fairchild's book [13] for more information on color appearance modeling.

The tone mapping operator by Ferwerda et al. [15] captures changes in threshold color appearance by using separate TVI functions for rods and cones and interpolation for the mesopic luminance range. Ward et al. [37] used a very similar approach in their work. Pattanaik et al. [25] proposed a comprehensive multi-scale model that accounts for changes both in threshold color discriminability and suprathreshold colorfulness. Using opponent color processing, the model is able to handle changes in chromatic and luminance-level adaptation as well. In their recent work, Reinhard and Devlin [27] adapted a computational model of photoreceptor behavior that incorporates a chromatic transform that allows the white point to be shifted.

4.4 Reproduction of details

The reproduction of details is an issue mainly in very dark and very bright areas, because truncation of values occurs most frequently in these areas as a result of limitations of the output device. The simplest methods (e.g., linear scaling or clamping) will usually reduce or destroy important details and textures (see Fig. 1). On the other hand, the effort to reproduce details well is a potential cause of *artifacts*.

Figure 1. Reproduction of details in a very bright area. Left: global tone mapping operator exhibits the loss of details. Right: details preservation owing to mapping by a local operator.

Several tone mapping operators focus especially on the reproduction of details. Tumblin and Turk's LCIS operator [35] produces a high detail, low contrast image by compressing only the large features and adding back all small details. The idea of compressing just the large features and then adding subtle non-compressed details is also used in the operators based on the bilateral [12] and trilateral filter [6].

A different approach was presented by Ward [37]. Ward's operator based on histogram adjustment aims to preserve *visibility*, where visibility is said to be preserved if we can see an object on the display if and only if we can see it in the real scene. Ward's operator does not strive to reproduce all the details available, but exploits the limitations of human vision to reproduce just the *visible* details. Also, most local tone mapping operators try to preserve detail along with contrast.

4.5 Special attributes

The following image attributes show up just under special conditions and we do not consider them in our current experiments, in favor of the basic ones. However, we present these attributes here to complete the survey of image attributes for tone mapping and it will be an interesting task to include them in future evaluations using all of the components of Fig. 2.

Visual acuity is the ability of the human visual system to resolve spatial detail. The visual acuity decreases in dark, since cones are not responding to such low light levels. It is interesting that simulating this phenomenon, i.e., reducing the detail in an image, actually enhances the *perceptual quality* of the image.

Owing to the scattering of light in the human cornea, lens, and retina, and due to diffraction in the cell structures on the outer radial areas of the lens, phenomena commonly referred to as **glare effects** [32] are seen around very bright objects. Since the dynamic range of traditional output devices is not sufficient to evoke such phenomena, we must simulate the human response artificially to improve the *perceptual quality* of the image.

As a consequence of tone mapping, **artifacts** may appear in the output image. The artifacts are degrading the *overall quality* of the output image. Some local tone mapping operators [5, 31] exhibit typical *halo artifacts*, see [29]. Another possible artifact of tone mapping methods stems from the superficial handling of colors. Many tone mapping methods use very simple rules in handling of the colors, i.e., doing the HDR to LDR transformation just for the luminance component with consequential restoration of the color information. Apart from poor values for the color reproduction image attribute, this can also lead to visible *color artifacts* like oversaturation. Closely related to color artifacts are *quantization artifacts*, especially in dark regions, which stem from applying transformations (like gamma correction) to a low-precision representation of color values.

5 Attribute relationships

In the previous sections, we have surveyed the image attributes that are important for tone mapping and influence the overall quality of the output image. Since these attributes are not independent, we present a description of their interrelationships in this section.

We propose the scheme shown in Fig. 2 to illustrate the relationships between the attributes. The **overall image quality**, our measure, is determined by all the attributes. It depends strongly on the overall perceived *brightness*, i.e., highly illuminated scenes should be reproduced bright, while dim scenes should appear dark. Apparent *contrast* should also be reproduced well to make the result natural. The reproduction of *details* or rather the reproduction of *visibility* of objects is certainly essential to make the output image appear natural. Furthermore, since we are typically facing a limited display gamut, the reproduction of *color* is

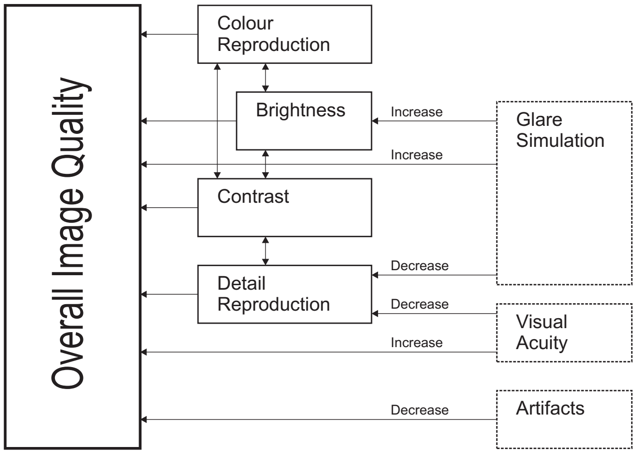


Figure 2. The relationships between image attributes. The attributes we did not evaluate in subjective testing are in dashed boxes.

an important factor for perceptual quality as well. The simulation of *visual acuity* loss can significantly improve the perceptual quality of dim or night scenes, while the simulation of *glare* can enhance the perceptual quality of the dark scenes with strong light sources. There is no doubt that the presence of disturbing *artifacts* degrades perceptual quality. But there are also important interrelationships of the attributes:

The perception of **brightness** is affected greatly by the *contrast arrangement* (i.e., by the semantics of an image). Fairchild [13] described the effect of image contrast on the perceived brightness and concluded that the brightness typically increases with *contrast*. It has been shown that brightness increases as a function of chroma (Helmholtz-Kohlrausch effect). Moreover, the simulation of color appearance at scotopic levels of illumination can substantially change the perceived brightness. Finally, the *simulation of glare* plays an important role for the brightness perception. The glare simulation increases the apparent brightness of light sources.

It was shown that **contrast** increases with the *luminance* (Stevens effect, see [13]). Since we can identify the contrast on different spatial resolutions, the perception of contrast is obviously affected by the reproduction of *details*. The experimental results of Calabria and Fairchild [4] confirmed that the perceived contrast depends also on image *lightness, chroma* and *sharpness*.

Colors are related to brightness, because the colorfulness increases with the luminance level (i.e., the Hunt effect [13]).

The reproduction of **details** is strongly affected by the simulation of the *visual acuity*. Since there are available data that represent the visual acuity (e.g., Shaler's curve), these data place limits on the reproduction of fine details, and may also be utilized to verify the perceptual quality of detail reproduction. Furthermore, the *visibility preservation* diminishes the reproduced details using a threshold function (e.g., the threshold versus intensity curve, TVI). The simulated *glare* can obscure otherwise reproducible details near strong light sources.

Using subjective testing results, Spencer et al. [32] verified that the **simulation of glare** can substantially increase the apparent *brightness* of light sources in digital images.

In the scheme of relationships (Fig. 2), we can identify attributes that represent **limitations** of the human visual system: the simulation of glare, the simulation of visual acuity and (in part) the reproduction of color (in the sense of simulation of the scotopic vision). These attributes enhance the perceptual quality of the output image, but are not desirable when the goal is different, for example when we aim to reproduce as many details as possible.

6 Subjective perceptual studies

We have conducted two separate subjective perceptual studies to encourage the proposed idea of an *overall image quality* measure and to verify the correlations to and between the image attributes shown in Fig. 2. Moreover, the execution of two principally different studies gave us the opportunity to relate the obtained subjective results.

Prior to the main experiments we have conducted a pilot study to examine the setup and to verify that subjects are able to rank soft-copy images against the real scene. During this study we have also fine-tuned the parameters of several tone mapping operators. Preliminary ideas of the project as well as the results of our pilot study have been presented recently [3].

6.1 Subjective testing setup

In the first experiment, based on **rating**, we simultaneously presented an original (real) HDR scene and the appropriate tone mapped image of this scene to human observers. We arranged a typical *real* indoor HDR scene, see Tab. 1. Then we acquired a series of 15 photos of the scene using a digital camera with varying exposition from a locked-down tripod. The HDR radiance map was recovered from the recorded series using the method by Debevec and Malik [8]. The dynamic range of the resulting HDR image was about $10^5 : 10^{-1}\mathrm{cd/m}^2$. Afterwards, we tone mapped this HDR image using 14 different tone mapping operators, so that we obtained 14 LDR images[1] for investigation.

[1] All the tone mapped images as well as the original HDR image are available on the web pages of the project: `http://www.cgg.cvut.cz/~cadikm/tmo`

We included the following operators into our experiment—the methods proposed by: Ashikhmin [2], Chiu et al. [5], Choudhury and Tumblin [6], Drago et al. [11], Durand and Dorsey [12], Fattal et al. [14], Tumblin and Turk [35], Pattanaik and Yee [24], Reinhard et al. [28], Schlick [31], Tumblin and Rushmeier's revised operator [33], Ward [36], Ward et al. [37], and a simple linear mapping; see Tab. 1. All the evaluated methods were implemented by the first author with some discussions and help from the original authors of these methods.

This sequence of 14 LDR images represented the input visual stimuli for each observer; the images were shown in random order. In the perceptual test arrangement the subject was able to observe both the real scene and a LDR image of the scene displayed on the calibrated CRT monitor. The testing was performed in a dark test room under controlled ambient luminance level. A total number of 10 subjects aged between 26 and 52 were asked to express the overall image quality, and the four basic attributes brightness, contrast, reproduction of details, and reproduction of colors for a particular image by *ratings* (on the scale 1–14, where 1 represents the best result, while 14 is the worst) with respect to the actual scene. Subjects had normal or corrected-to-normal vision and were non-experts in the field of computer graphics.

In the second experiment, based on **ranking**, we investigated what happens when subjects have no possibility of directly comparing to the ground truth (or are not affected by a previous experience with the real scene). A group of 10 observers (different ones than in the first experiment), who have never seen the real HDR scene and had therefore virtually no idea about the original scene attributes, was selected. This group comprised persons aged between 25 and 45, male and female, and all were non-experts in computer graphics. The task of each subject was to order (*rank*) *image printouts* resulting from the 14 operators according to the overall image quality, and the quality of overall contrast, brightness, color and detail reproduction. The investigated printouts were high-quality color image printouts on a glossy paper of the same 14 tone mapped images as in the first experiment.

7 Results and discussion

The results obtained from the two different experimental approaches are summarized in Tab. 1 and Fig. 3. Our investigations are formulated by means of these results in four-dimensional functions, namely as the dependence of the overall image quality on the brightness, the contrast, the color and the detail reproduction attributes. We have compared the results of *rating* and *ranking* methods. Rating had to be chosen for the first experiment because the 14 images could not be shown simultaneously with the reference scene. The rating scale was chosen so that the scores were in the interval same interval ($[1, 14]$), as the ranking values.

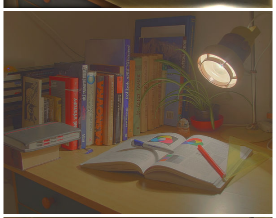
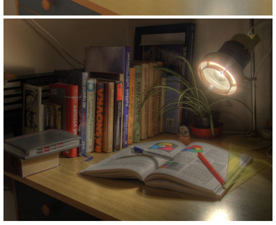
The basic difference between the two approaches is that in the case of very similar images, the rating gives very similar non-integer numbers, while for ranking, always all integer values are distributed from 1 to 14. In our case the attributes have a relatively uniform distribution, thereby this problem was not critical. However, the nature of rating is generally more uncertain than the one of ranking, because the pure comparison of images is subjectively easier than to specify quantitative values.

We averaged the results of all observations for both the ranking and rating experiments, i.e., we obtained non-integer numbers. Fig. 3 shows these average results for the overall image quality and for all the investigated image attributes. Although the original high dynamic scene was used for the rating, and the ranking was carried out using only the resulting images of the different tone mapping methods, the basic trends are rather similar than contradictory. For all of the attributes, except the brightness, the rating and ranking results exhibit high correlations, around 0.7, that means that people judge the quality of tone mapped image in both cases very similarly. On the other hand, the brightness attribute shows correlation coefficient of 0.49 which denotes that the direct comparison with the real scene has an important influence on the perception of the quality of brightness reproduction. The two experimental approaches together help in a more deeper understanding and evaluation of the qualities and methods. Beyond Fig. 3, we can observe this on Tab. 1 as well.

The results of both experiments show that the *best overall quality* is exhibited by the method of Reinhard et al. [28], the second one is the global mapping of Ward el al. [37], while the worst is an early local approach by Chiu et al [5]. At the bounds of the quality interval, the best and the worst methods exhibit also the lowest variance, while the middle zone with often uncertain judgments has higher variances. The observers have typically the same opinion about the best/worst question, but difficulties with the evaluation of some similar cases. All of the values on the Fig. 3 and in the Tab. 1 are the average values of the two independent groups of ten and nine observers respectively.

7.1 Comparison to other studies

In this section we discuss and compare our results to other studies. We should emphasize here that this study was targeted to the natural reproduction of a real scene, and with 14 involved operators presents one of the most comprehensive evaluations yet. Complete direct comparison of the results is therefore not possible. Since our experimental input data are bound to natural indoor scenes, the global tone mapping methods (and local methods with a proper global

Method	Image	Bright.	Contrast	Details	Colors	Quality Overall
[2]		**6,70** *2,53* **7,40** *2,88*	**7,00** *3,72* **7,20** *3,17*	**4,80** *2,64* — **6,10** *2,86*	**6,70** *3,23* **7,80** *3,32*	**7,40** *3,26* **7,00** *2,42*
[5]		**13,90** *0,30* **10,03** *2,72*	**12,30** *3,00* **9,33** *3,50*	**12,00** *2,53* — **8,28** *3,51*	**13,90** *0,30* **8,17** *2,06*	**13,20** *1,25* **10,97** *2,24*
[6]		**9,80** *1,47* **5,80** *3,37*	**9,10** *2,34* **6,20** *3,95*	**8,00** *2,57* — **5,30** *3,39*	**9,60** *1,36* **6,40** *3,78*	**11,40** *2,15* **5,40** *3,74*
Linear Clip		**4,40** *2,84* **7,00** *1,77*	**7,40** *3,98* **6,07** *1,70*	**7,40** *4,70* — **8,17** *2,45*	**3,70** *3,64* **4,90** *1,93*	**6,10** *3,02* **7,70** *1,17*
[11]		**4,10** *1,51* **6,20** *2,90*	**5,50** *1,80* **6,80** *2,20*	**7,40** *2,65* — **8,30** *2,72*	**6,00** *3,00* **6,20** *2,27*	**6,10** *1,45* **6,80** *2,73*
[12]		**6,60** *3,70* **9,33** *2,11*	**10,30** *4,36* **9,57** *1,86*	**8,10** *3,96* — **7,70** *2,12*	**10,40** *2,87* **9,80** *1,98*	**11,50** *2,66* **9,80** *1,98*
[14]		**11,80** *0,98* **9,00** *1,96*	**9,60** *3,61* **9,00** *2,12*	**7,60** *4,22* — **6,10** *3,31*	**10,00** *1,84* **9,80** *2,56*	**9,20** *2,40* **9,40** *3,40*

Method	Image	Bright.	Contrast	Colors	Details	Quality Overall
[35]		**10,90** *1,51* **4,60** *2,99*	**8,80** *2,60* **5,20** *3,20*	**9,60** *3,90* — **5,30** *3,40*	**11,60** *1,20* **5,60** *3,61*	**10,40** *1,28* **4,40** *4,08*
[24]		**3,90** *3,59* **4,90** *3,16*	**6,10** *3,59* **4,43** *2,06*	**2,60** *2,54* — **3,70** *3,24*	**6,40** *3,32* **4,90** *2,62*	**8,20** *3,31* **5,60** *3,43*
[28]		**4,20** *1,89* **3,20** *1,56*	**3,40** *2,69* **2,80** *1,62*	**4,60** *2,80* — **3,03** *1,77*	**2,50** *1,43* **2,40** *1,33*	**2,80** *1,08* **2,60** *1,88*
[31]		**11,20** *2,36* **6,53** *3,50*	**7,90** *3,33* **4,90** *3,40*	**8,80** *3,76* — **5,95** *4,12*	**9,40** *2,87* **4,20** *3,31*	**5,70** *3,13* **5,37** *3,90*
[33]		**3,90** *1,58* **5,60** *1,77*	**5,50** *3,26* **5,37** *2,06*	**7,50** *3,91* — **6,65** *1,71*	**4,70** *1,90* **3,27** *1,14*	**4,20** *3,06* **6,30** *2,12*
[36]		**7,30** *3,04* **7,60** *2,78*	**6,90** *4,04* **4,80** *2,12*	**9,70** *1,90* — **7,50** *1,77*	**5,40** *2,38* **4,00** *1,88*	**5,30** *3,74* **6,20** *2,41*
[37]		**6,20** *2,49* **4,60** *2,24*	**5,20** *3,28* **5,20** *2,88*	**6,90** *3,24* — **5,70** *1,05*	**4,70** *2,28* **4,00** *2,20*	**3,50** *1,80* **3,80** *1,93*

Table 1. Strengths and weaknesses of 14 essential tone mapping methods. Average ranking scores in bold (1st line) and average rating scores (3rd line) with standard deviations (in italics) for each method (1 is the best, 14 the worst).

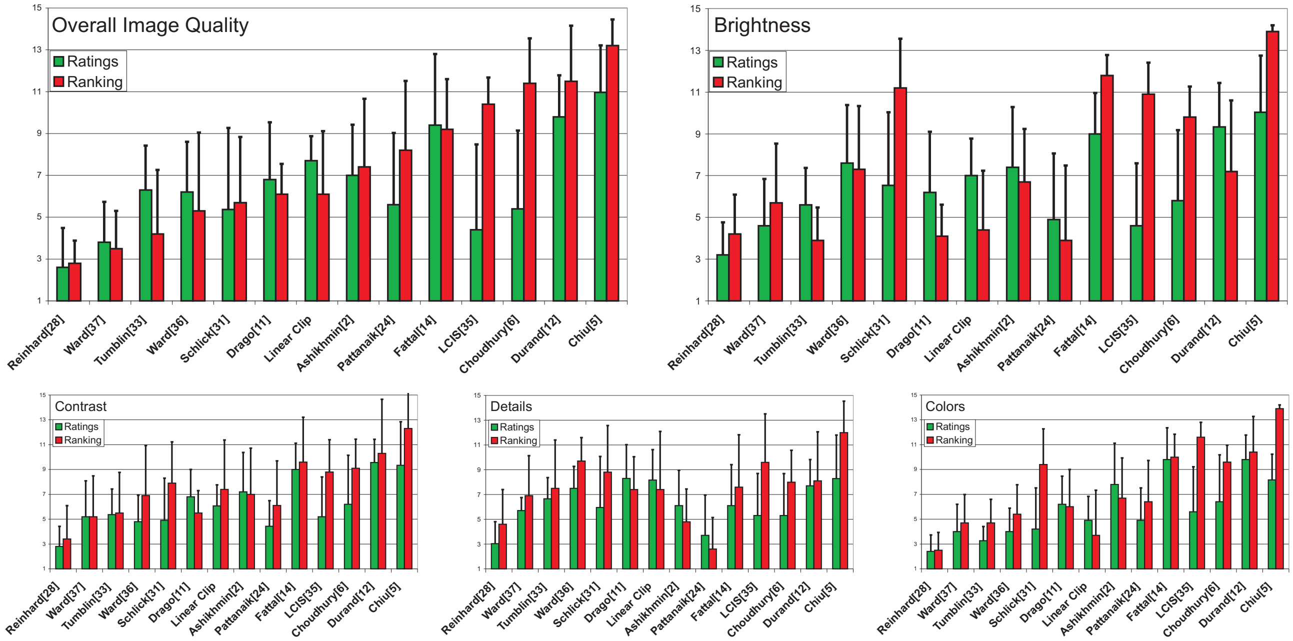


Figure 3. Comparison of average scores (visualization of data from Tab. 1). The charts show evident coherence in the results obtained using the 'to the reality comparison', expressed by ratings (green), and by the 'ordering', ranking (red) (1 is the best, 14 the worst). Black abscissae at top of bars represent the values of appropriate standard deviations.

part) were generally ranked better than the 'detail-hunting' and non human vision-aware approaches. The quality of reproduction of overall brightness, contrast and colors is more important than the reproduction of details when naturalness is ranked in real scenes. This observation is numerically supported by the analysis presented in the next section.

Our results are in a good agreement with the evaluation by Drago [10]: Reinhard's operator is ranked the best and Schlick's method is ranked also very good in their study. The difference is in Ward's histogram-based approach, where authors deliberately omitted the human-based ceiling function and therefore the operator favours the reproduction of details at the expense of naturalness. The consequences of Kuang [19] are also similar to ours: Fattal's operator was considered not very natural while the Reinhard's photographic mapping was nearly the best ranked. The difference is with the bilateral filtering operator. We believe this is caused by the implementation of the global part of tone mapping function. We, in accordance with the original method description [12], have compressed the base layer using a scale factor in the log domain. More plausible global compression (e.g., the S-shaped curve) would result in a positively better outcome, but we were targeted to compare purely the original approaches. This supposition is also well supported by the conclusions of Ledda et al. [20], where the bilateral filtering approach performed the worst and other overlapping operators show perfect agreement as well (in the overall similarity test).

7.2 Overall image quality

Beyond the discussed general results, we analyzed the *dependencies of overall image quality* on the four selected basic perceptual image attributes. We used different methods to fit functions to the brightness, contrast, detail and color attributes judgment values receiving the best approximation to the independently observed overall image quality. Using the simplest approach, *linear regression*, we obtained the following result:

$$\mathrm{OIQ} = 0.327 \cdot \mathrm{Bri} + 0.267 \cdot \mathrm{Con} + 0.102 \cdot \mathrm{Det} + 0.230 \cdot \mathrm{Col}, \quad (1)$$

where OIQ is an overall image quality function in the interval of $[0,1]$ (1 being the best quality), Bri is brightness, Con is contrast, Det are details, and Col are colors, all in the interval of $[0,1]$ (0 meaning the worst reproduction of the appropriate attribute). We can observe that the *overall brightness* has the biggest weight and the detail reproduction the smallest one. This result may look surprising, as one would expect details to be more important. But the global appearance of an image seems to depend much more on other image attributes (brightness, contrast, color).

Furthermore, it is evident that the basic categories are very hard to separate. As we proposed in Section 5, there are cross effects, or more complex basic factors, which are not directly observable. However, we have not received a deeper result or new non-trivial basic attributes from our observations when carrying out a statistical factor analysis, thereby we do not deal with this question here.

For a more in-depth analysis of the data, we made experiments with other classes of functions. The generalization of the above linear regression is the linear combination of different *power functions* of the image attributes. With non-linear optimization we received optimal fitting function to the overall quality that can be expressed as:

$$\begin{aligned}\mathrm{OIQ} = 2.315 \cdot \mathrm{Bri}^{0.350} + 0.855 \cdot \mathrm{Con}^{0.377} + \\ + 0.065 \cdot \mathrm{Det}^{0.354} + 0.609 \cdot \mathrm{Col}^{0.354}. \qquad (2)\end{aligned}$$

Here, the minimal standard error of estimate was 4.162, while in linear regression (1), which is a special case of (2), the error was 4.492. In (2) we can observe a similar ranking of importance of the basic attributes as in the linear case. The brightness is the most important, contrast and color reproduction are not significantly, but evidently somewhat less important, while the smallest term is the detail reproduction, here as well.

We looked for a good fitting also in form of a *multiplicative function*, with unknown powers and a free calibration multiplier. The result—obtained on a log scale with linear regression—is as follows:

$$\mathrm{OIQ} = 4.987 \cdot \mathrm{Bri}^{0.135} \cdot \mathrm{Con}^{0.021} \cdot \mathrm{Det}^{0.002} \cdot \mathrm{Col}^{0.047}. \quad (3)$$

Since both non-linear formulas (2, 3) show a similar tendency as the result of linear regression (1), we propose to use this simplest formula.

In the future, we will take into consideration all of the mentioned image attributes (Fig. 2), with the aim of finding a general optimal nonlinear fitting for a wide class of HDR images with numerous observers. However, even the analysis of basic image attributes resulted in new and interesting insights about their importance and correlation, which can be used in future tone mapping evaluations.

8 Conclusions

In this paper, we presented an overview of image attributes for tone mapping that should facilitate access to the existing tone mapping literature. Since the attributes are intimately related, we have proposed a scheme of relationships between them. Moreover, we have proposed a measure for the *overall image quality*, which can be expressed as a combination of these attributes based on psychophysical experiments. We have verified the proposed ideas by means of two different psychophysical experiments.

The presented overview of image attributes is helpful for getting into the tone mapping field, or when implementing or developing a new tone mapping operator. On the other hand, the identification of the relationships between the attributes is very useful for the subjective comparison of tone mapping methods. It also simplifies the comparison process by reducing the actual number of attributes that can be used to evaluate a tone mapping operator. Finally, it represents the initial effort to design a truthful, objective comparison metric for high dynamic range images.

An interesting outcome of the two different testing methodologies used (rating and ranking) is that almost all of the studied image quality operators can be evaluated without comparison to a real HDR reference. This paper presents one of the most comprehensive evaluations of tone mapping operators yet, with 14 different tone mapping methods evaluated using the results of two different experimental studies.

The question remains how to numerically assess particular image attributes. Although some approaches were proposed in history [16, 22] this area deserves further investigation and subjective verification. In the future, we will conduct consequential subjective tests targeted on individual image attributes to be able to computationally assess the overall quality of tone mapping. Finally, since we used a limited span of input images, more thorough and extensive testing is needed to confirm the applicability of the outlined results to other types of scenes.

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