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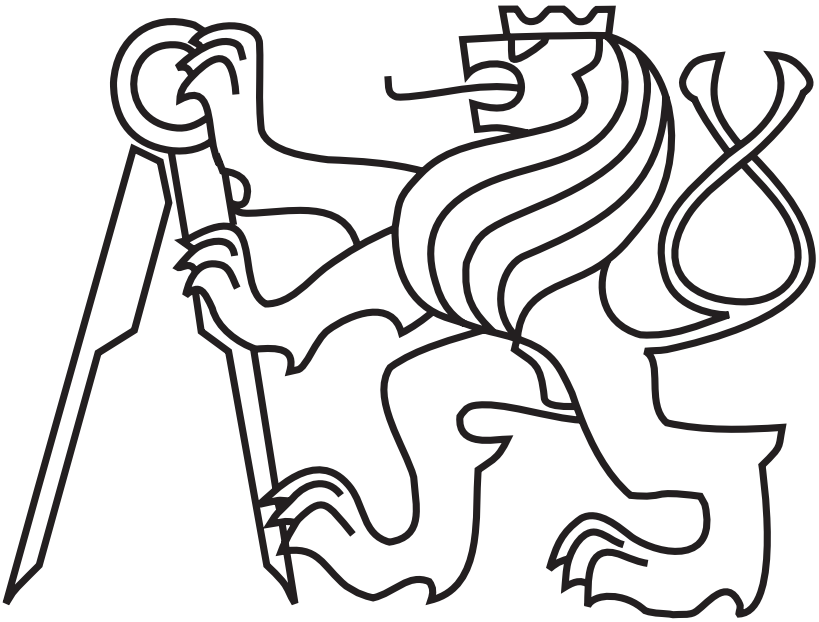

Doctoral thesis statement

Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Computer Science and Engineering

Perceptually Based Image Quality Assessment and Image Transformations

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A doctoral thesis submitted to
the Faculty of Electrical Engineering, Czech Technical University in Prague,
in partial fulfilment of the requirements for the degree of Doctor.

Ph.D. Programme: Electrical Engineering and Information Technology
Branch of study: Information Science and Computer Engineering

January 2008

This doctoral thesis was carried out as a part of a full-time Ph.D. study at the Department of Computer Science and Engineering of the Faculty of Electrical Engineering of the Czech Technical University in Prague.

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Prof. Ing. Pavel Tvrdík, CSc.

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Contents

1 Introduction

Visual perceptions are remarkably significant for human beings. We resolve various everyday issues, we gain a lot of knowledge, and we amuse ourselves thanks to our vision. Human visual system (HVS) is an extremely evolved part of the nervous system that interprets the information from visible light to enable us to see. Although the complex HVS that constitutes considerable piece of the brain excellently carries out visual tasks, it has its specific features, sometimes referred to as HVS limitations. Since outputs of computer graphics and digital image processing methods are observed by human subjects, such methods can and have to reflect the features of the HVS to generate perceptually correct and plausible images and to improve the performance. The knowledge of the HVS usually takes the form of *computational models* and these models can be incorporated at various areas of computer graphics and digital image processing. The fields where the utilization of HVS models becomes particularly beneficial and which we concern ourselves with in the thesis are image quality assessment, high dynamic range tone mapping, and color image to grayscale conversions.

1.1 Motivation

Even though the knowledge about the HVS is continually developing, many unanswered questions and hypotheses still remain to be solved. On that account, we are quite far from having an accurate computational model of the HVS. It is therefore of particular importance and necessity to conduct *experimental subjective evaluations* of the computational approaches that incorporate HVS models to judge and validate them properly. Moreover, the evaluations give us a deeper insight into the inquired area and besides the evaluation of existing methods, they can lead to *proposals of new ones*.

1.1.1 Image Quality Assessment

The goal of *Image Quality Assessment* (IQA) is to computationally predict human perceptions of the image quality. It is known [Teo94] that classical metrics like Root Mean Squared (RMS) error are not adequate to the comparison of images, because they poorly predict the differences between the images as perceived by the human observer. To solve the problem properly, various perceptual *Image Quality Metrics* (IQM) have been proposed. Image quality metrics traditionally comprise a computational HVS model to correctly predict image difference as a human would perceive it. In the thesis, we concern ourselves with *full-reference image quality metrics* that assume that a complete reference image is known. The

input to the full-reference IQM includes two images (e.g. a reference image and a distorted image), whereas the output is a map describing the visible differences between them, see Figure 1.1.

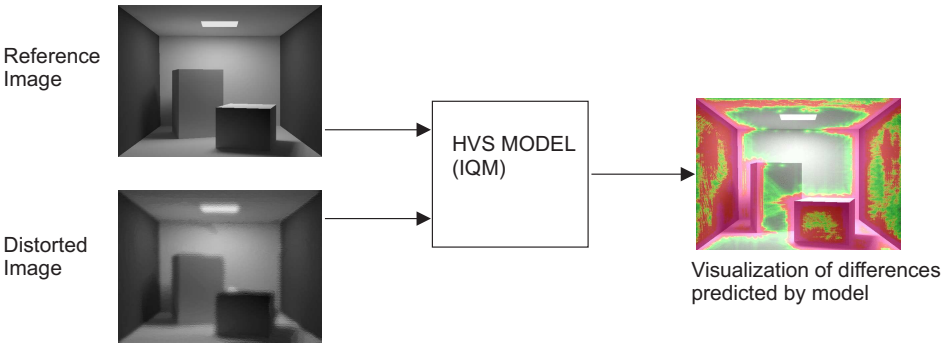

Figure 1.1: Full-reference image quality metrics.

Image quality assessment is very practical in various imaging applications. The main domains of IQA lie in the areas of monitoring of image quality (e.g. in lossy image compression), benchmarking of imaging applications, and optimizing algorithms and their parameter settings. However, image quality metrics have successfully been applied also to image database retrievals, to the evaluation of the perceptual impact of different rendering algorithms, to the perception-guided rendering of animations, etc.

1.1.2 High Dynamic Range Tone Mapping

High Dynamic Range (HDR) images are becoming widespread in many imaging areas thanks to the uniquely high range of values (luminances) and the high numerical precision. One may acquire an HDR image synthetically (e.g. utilizing a physically-based renderer), by means of a specialized HDR camera, or using series of ordinary images captured with varying exposure by a consumer-level digital camera. The HDR image can comprise vast range of luminances (typically the whole range of a real-world scene), and the challenge is how to display it on devices with limited (Low) Dynamic Range (LDR). This problem is called an *HDR tone mapping* and various methods have been proposed to solve it [Devl02, Rein05].

Tone mapping methods (sometimes called Tone Mapping Operators – TMOs) take an HDR image on input and reduce (transform) its range to an ordinary (LDR) image, see Figure 1.2. The goal of many tone mapping methods is to perform the

transformation in a way that corresponds to human perception of a scene captured in the input HDR image. Accordingly, many tone mapping methods mimic the behavior of the human visual system. As we currently register several dozens of tone mapping approaches whose merits and shortcomings are not immanently clear, an experimental validation and evaluation of them is needed.

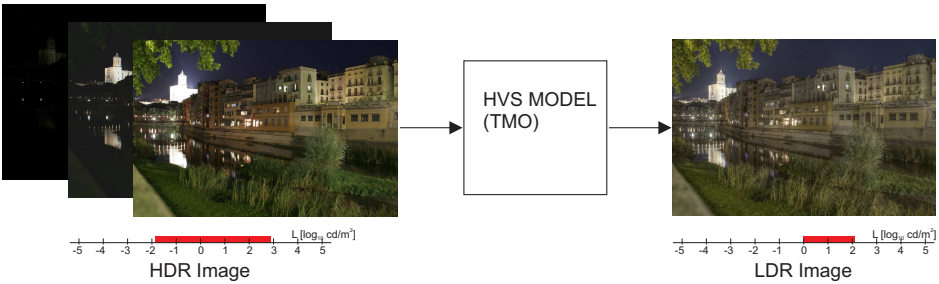

Figure 1.2: High dynamic range tone mapping.

1.1.3 Color to Grayscale Conversions

Color images often have to be converted to grayscale for reproduction or for subsequent processing. Methods performing *color to grayscale conversion* do basically a reduction of three dimensional color data into one dimension, see Figure 1.3. The aim of color to grayscale conversions is usually to produce perceptually plausible grayscale results. Unfortunately, an analogous conversion is not naturally present in the HVS. However, one may measure perceptual differences between colors in subjective psychophysical experiments. Moreover, it is evident that some loss of information due to the conversion is inevitable, so that the other goal is to save as much information contained in the original color image as possible. The complexity of the color to grayscale conversion issue is known, but the existing approaches [Gooc05, Rasc05] are eminently computationally intensive, which does not make them suitable for interactive conversions or conversions of high resolution images.

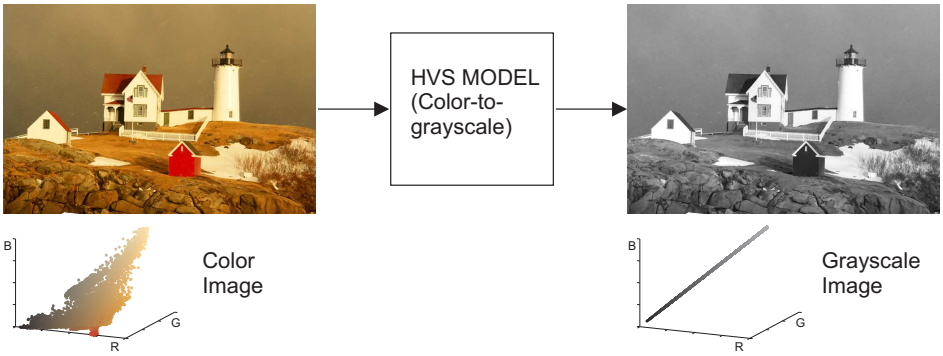

Figure 1.3: Color image to grayscale conversion.

1.2 Aims of the Thesis

The thesis aims to provide the following contributions:

- Presentation and discussion of the results of subjective experiment that we have performed to *compare and evaluate traditional error sensitivity based and structural similarity based approaches* to the image quality assessment. A survey and the description of existing methods of the two groups (Chapter 3 of the thesis).

- A study about the effects of basic *image attributes for HDR tone mapping* and a survey how different methods reproduce these attributes. Proposal of a scheme of *relationships between essential image attributes*, leading to the definition of an overall image quality measure (Chapter 4 of the thesis).

- Presentation and discussion of the results of two different subjective psychophysical experiments that we have performed to prove the proposed relationship scheme of image attributes. Moreover, the presentation of an *evaluation of fourteen existing tone mapping methods* with regard to these image attributes (Chapter 4 of the thesis).

- A new perceptually plausible, fast and simple yet powerful general *hybrid approach to HDR tone mapping*. The new approach applies a global tone mapping method first to reproduce overall image attributes correctly and to construct an enhancement map to guide a local operator to the critical areas that deserve local enhancement. The new approach is general and can

be easily tailored to miscellaneous goals of tone mapping (Chapter 5 of the thesis).

- Two new perceptually convincing local *color to grayscale conversion techniques*. One is based on the CIELab color difference formula, and the other on the Coloroid system and its experimental background (Chapter 6 of the thesis).
- A new and efficient way of converting an inconsistent gradient field into a consistent one, which can be directly converted into an image by a simple 2D integration. The complexity of this method which we call *gradient inconsistency correction* is linear in the number of pixels, making it suitable for high-resolution images (Chapter 6 of the thesis).

2 Related Work

This chapter concisely reviews the works related to the topics we concern ourselves with in the thesis.

2.1 Image Quality Assessment

Traditional perceptual image quality assessment approaches are based on measuring the errors (signal differences) between somehow distorted image and the reference image, and attempt to quantify the errors in a way that simulates human visual error sensitivity features. A great variety of image quality metrics has been proposed in the literature. For many of these models, common computational parts can be identified [Wang03]. These parts are: preprocessing, Contrast Sensitivity Function (CSF) filtering, channel decomposition, error normalization and masking, and finally the error pooling. Most of the approaches incorporate only a few of many factors that influence visual perception, typically just the luminance adaptation and the contrast sensitivity. Moreover, contemporary image metrics typically consider the image as a whole. Therefore, the results of these metrics in the comparison of images with *Regions Of Interest* (ROI), e.g. the JPEG 2000 [Taub02] ROI compressed images, are uncertain. Since the number of published image quality metrics is considerable, evaluation and comparison of them become an important issue. However, only a few *comparative studies* exist that have investigated the prediction accuracy of metrics in relation to others.

Differently from the traditional error sensitivity based approach, *structural similarity based image quality assessment* has been proposed [Wang02, Wang04]. Structural similarity approach to the IQA is based on the philosophy that the main function of the human visual system is to extract structural information from the viewing field, and that the human visual system is highly adapted for this purpose. Therefore, a measurement of structural information loss can provide a good approximation to the perceived image distortion. A specific example of the structural similarity quality measure is the Structural SIMilarity Index (SSIM) [Wang04]. The SSIM separates the task of similarity measurement into three comparisons, the luminance comparison, the contrast comparison, and the structure comparison. The three components are then combined to yield an overall similarity measure.

2.2 High Dynamic Range Tone Mapping

Merits of High Dynamic Range Imaging (HDRI) are currently widely recognized in computer graphics, high-quality photography, computer vision, and other areas of digital imaging. Moreover, HDRI becomes popular in interactive and real-time applications as well. Data visualizations, computer games and other interactive applications gain new qualities thanks to the HDRI.

Several dozens of so-called tone mapping methods were proposed in history, see surveys in [Devl02, Rein05]. One can classify the existing tone mapping approaches according to the transformation they apply to convert input luminances to the output values. *Global tone mapping methods* apply the Tone Reproduction Curve (TRC), i.e. a function. Therefore, they transform particular value of the input luminance to one specific output value. *Local tone mapping methods* (Tone Mapping Operators – TMOs) may on the other hand reproduce particular input luminance to different output values depending on the surrounding pixels.

Generally speaking, global methods (TRC), e.g. [Ward94, Tumb99b, Lars97, Drag03a], reproduce overall image attributes well, they are fast to compute, and easy to implement, but may wash away important details. Local approaches (TMO), e.g. [Rein02, Schl94, Dura02, Tumb99a, Patt02, Chou03, Ashi02, Fatt02, Chiu93], on the other hand excel in reproduction of local contrast (details), but they are computationally intensive and may reproduce overall image attributes poorly.

2.3 Color to Grayscale Conversions

Conversion from color to grayscale is an important piece of the digital imaging puzzle. In conventional black-and-white photography tones are determined by the spectral sensitivity of the emulsion, and can be varied in an active way by selecting different filters to enhance one part of the spectrum. This analog multispectral technique can now be emulated by digital image processing, and this approach to the problem can be considered as a 'global' technique.

An alternative, spatial approach to color to grayscale conversion has been proposed by Bala and Eschbach [Bala04]. They preserve chrominance edges locally by introducing high-frequency chrominance information into the luminance channel. A spatial high-pass filter is applied to the chromatic channels, the output is weighted with a luminance-dependent term, and the final result is added to the luminance channel.

Grundland and Dodgson [Grun05] proposed the Decolorize algorithm for contrast enhancement as well as color to grayscale conversion. They perform

a global grayscale conversion by expressing grayscale as a continuous, image-dependent, piecewise linear mapping of the RGB primary colors and their saturation [Grun05].

A somewhat different approach was taken by Gooch et al. [Gooc05], who introduced the pioneering local algorithm known as Color2Gray. In this gradient-domain method, the gray value of each pixel is iteratively adjusted to minimize an objective function based on local contrasts between all the pixel pairs. Unfortunately, the complexity of the method is very prohibitive $O(N^4)$, which can be improved by limiting the number of considered differences (e.g. by color quantization), however at the cost of possible artifacts.

Mantiuk et al. [Mant06] showed an application of their contrast processing framework for conversion of color images to grayscale. Their method is based on Gooch's [Gooc05] idea, but involves a more efficient approach, in which the close neighborhood of a pixel is considered on fine levels of a pyramid while far neighborhood is covered on coarser levels. Authors claim that this enables them to convert bigger images and perform computations faster, unfortunately no complexity analysis is reported.

Another conversion to grayscale that aims to preserve the contrast while maintaining consistent luminance was introduced by Rasche et al. [Rasc05], who approached the problem by means of a constrained multidimensional scaling. The execution time of this approach is highly sensitive to the number of colors. This can be ameliorated by color quantization [Rasc05], but it results in undesirable artifacts making the use of the method proposed by Rasche et al. very questionable for photographic images.

3 Summary of Results and Contributions

In the thesis, we present experimental subjective evaluations of image quality assessment metrics and High Dynamic Range (HDR) tone mapping methods. Furthermore, we propose new human perception motivated approaches to HDR tone mapping and to color to grayscale conversion. This chapter summarizes our contributions and discusses ongoing and potential directions of future work.

3.1 Perceptual Evaluation of Image Quality Metrics

In Chapter 3 of the thesis, we focus on methods for image quality assessment. We present results of the *evaluation of two principal approaches to the image quality assessment*. We evaluated the error sensitivity based approach and the structural similarity based approach using the representative models of each group: the Visible Differences Predictor [Daly93] (VDP) and the Structural SIMilarity index [Wang04] (SSIM). Inputs to the subjective experiments included *uniformly compressed* images and images compressed non-uniformly with *Regions Of Interest* (ROI), see Figure 3.1. We assess the performance of the selected models using subjective opinion scores obtained in both the uniform and the ROI compression experiments. We discuss obtained results, and point out the similarities and differences between the two approaches. Besides, we present a survey of published models of the two inquired groups.

Our results imply that the structural similarity approach overcomes the traditional error sensitivity based approach. Since the implementation of a structural similarity model is typically more straightforward than the implementation of an error sensitivity based model, we conclude that the structural similarity is a significant alternative to the thoroughly verified error sensitivity approach. Nevertheless, both inquired approaches perform poorly in the assessment of ROI compressed images.

3.2 Perceptual Evaluation of Tone Mapping Methods

In Chapter 4 of the thesis, we present a study about the effect of *basic image attributes* in the HDR tone mapping. We propose a scheme of relationships between these attributes and we present results of *subjective psychophysical experiments* that we have performed to prove the proposed relationship scheme. Furthermore, we present an *evaluation of existing tone mapping methods* with regard to these attributes. Differently from previous evaluations [Drag03b, Yosh05, Kuan06b], we adopted both the direct (with reference) comparison of tone mapped images to the

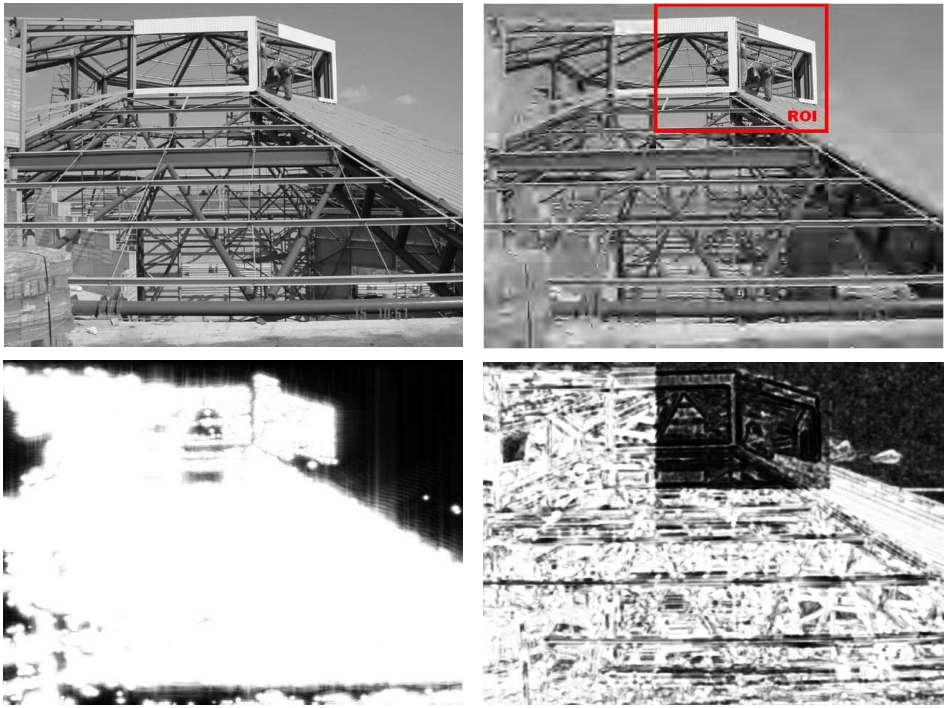

Figure 3.1: Example of image quality assessment using the VDP and the SSIM – ROI compressed image. Original image (top left), ROI compressed image (top right), VDP detection probability map (bottom left), SSIM detection probability map (bottom right). Probability maps: black pixel means zero probability of difference detection, white pixel means 100% probability.

real scenes, and the self-contained ranking without real references, see Figure 3.2. This enabled us to confront the results from these two experiments.

An interesting and important result of the two different testing methodologies used (rating with reference and ranking without reference) is that almost all of the studied image quality attributes can be evaluated without comparison to a real HDR reference. With 14 inquired methods (linear clipping and [Ward94, Tumb99b, Rein02, Schl94, Lars97, Dura02, Tumb99a, Patt02, Chou03, Drag03a, Ashi02, Fatt02, Chiu93]), and three typical real-world HDR scenes, the presented study is one of the most comprehensive evaluations of tone mapping methods. Another important outcome of our study is that the proper global part of a tone mapping method is essential to obtain good perceptual results for typical real

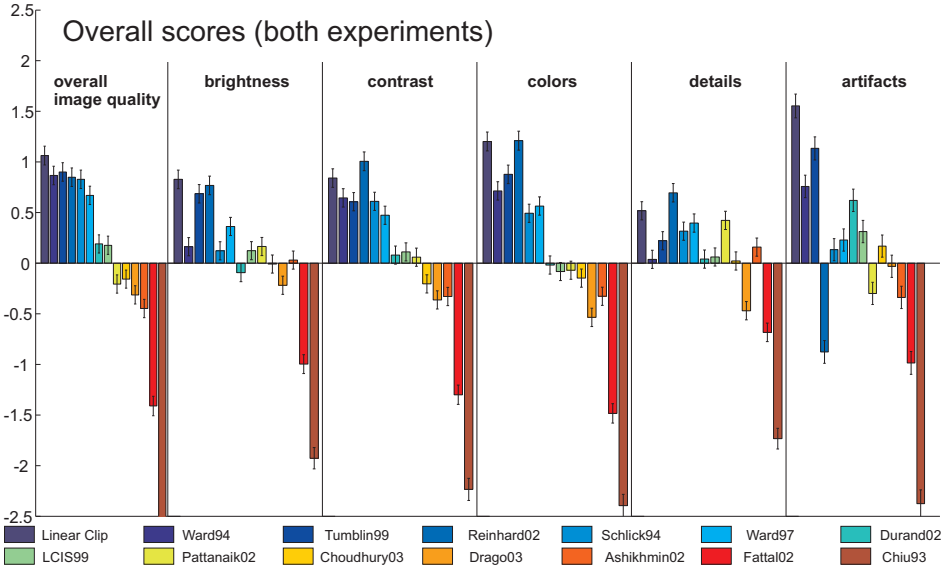

Figure 3.2: Overall accuracy scores for all examined TM methods. Left to right: overall perceptual quality, reproduction of brightness, reproduction of contrast, reproduction of details, reproduction of colors, lack of disturbing artifacts. In each chart the higher value represents the higher reproduction quality.

world scenes. Moreover, our effort is also useful to get into the tone mapping field or when implementing a tone mapping method, and it sets the stage for well-founded quality comparisons between tone mapping methods.

3.3 Hybrid Approach to Tone Mapping

In Chapter 5 of the thesis, we propose a novel simple yet powerful *general hybrid approach to the tone mapping* issue. In our approach, we combine outputs of arbitrary global and local Tone Mapping (TM) methods. Motivated by the results of conducted subjective experiments that have shown high importance of preservation of global image attributes, we apply the global method first to reproduce overall image attributes correctly. At the same time, we construct an enhancement map to guide a local operator to the critical areas of an image that deserve enhancement, see Figure 3.3. We do not invent another complex TM method, but we rather propose a general framework that utilizes already known

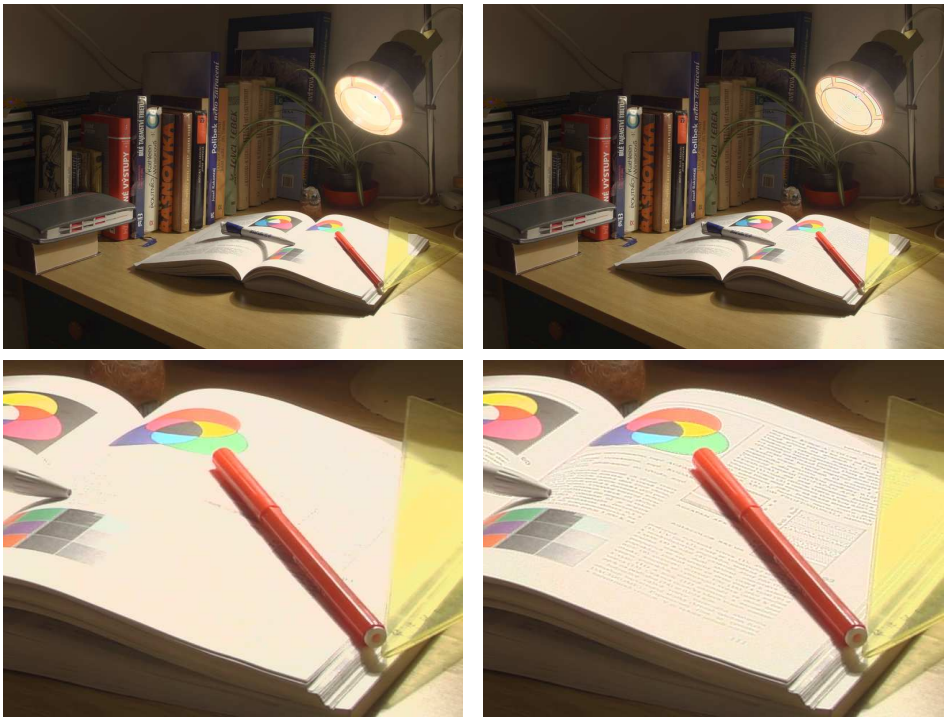

Figure 3.3: Top left: result of purely global method [Ward94] exhibits well reproduced overall contrast, however shows the lack of subtle details, top right: result of the new hybrid approach [Ward94, Dura02] preserves the overall contrast accurately, and adds the lost details. Bottom: close-ups of the book, note the reproduced details in the hybrid approach result.

ideas and combines existing and potentially forthcoming methods to obtain perceptually justifiable results. Based on the choice of involved methods and on the manner of construction of the enhancement map, we show that our approach is general and it can be easily tailored to miscellaneous goals of tone mapping. An implementation of proposed hybrid tone mapping produces plausible results, it is easy to implement, fast to compute and it is comfortably scalable. These qualities nominate our approach for utilization in perceptually oriented and time-critical HDR applications like HDR image viewers, modern computer games, interactive visualizations, mobile device HDR applications, etc.

Subsequently, Artusi et al. [Artu07b] published a concept of *selective tone mapper* which uses a model of visual attention to direct local TMOs to perceptually im-

portant parts of an image, while a global TM method is used for the remainder. Artusi et al. propose a generic GPU-aware implementation that can utilize any existing GPU TM methods. Factually, this work is an implementation and verification of the hybrid approach as was proposed in Chapter 5 of the thesis: authors utilize the Canny edge detection in the construction of the enhancement map (in their notation: important areas) and then, in accord with the hybrid approach, they apply local TM method just to these important parts of the image. As the reported computational and quality performance results are very promising they encouraged authors of the selective tone mapper to patent their work [Artu07a].

3.4 Perceptually-Plausible Conversion of Color Images to Grayscale

In Chapter 6 of the thesis, we propose a *new perceptually-plausible conversion of color images to grayscale* (see Figure 3.4) that operates in the gradient domain. We propose two novel and efficient ways to construct a gradient field from a color image. The first approach operates in the CIELab color space, while the second uses the Coloroid system [Nemc87], which is based on a strong experimental background. In this second approach we formulate, and obtain, perceptually justifiable gray gradients equivalent to different color attributes, by means of efficient experimental arrangements.

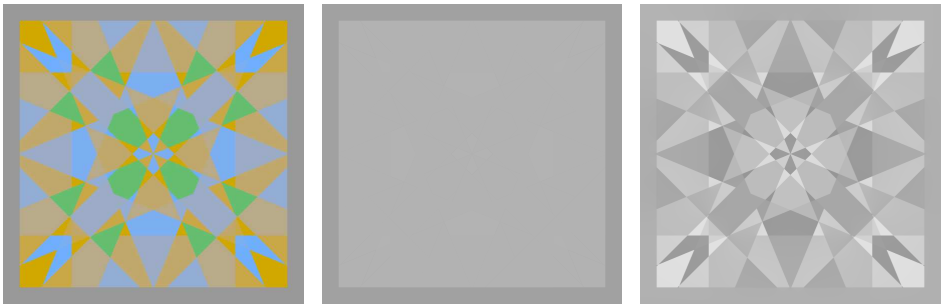

Figure 3.4: An artificial isoluminant image. Left: original color image. Center: CIE Y equivalent. Right: the result of our adaptive color-to-grayscale conversion.

Using one of the new approaches, we obtain an inconsistent gradient field from a color image. As the inconsistent gradient field does not correspond to any real image, the problem is how to transform it to an output grayscale image. For solving this gradient field inconsistency problem, we have introduced a *new gradient inconsistency correction method*, see Figure 3.5. This method works with

unknown gradients to obtain a consistent gradient field. Given an inconsistent gradient field, it can find the nearest consistent field in the linear subspace of consistent gradient fields. Having obtained a consistent gradient field, the final image can then be produced by two-dimensional integration. The method has linear complexity in the number of pixels, which makes it suitable for high-resolution images.

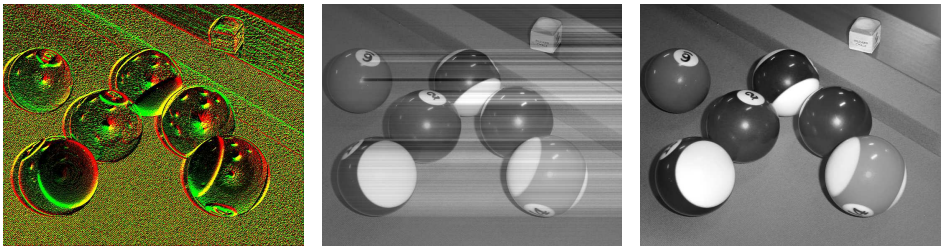

Figure 3.5: Left: visualization of an inconsistent gradient field. Center: the result of direct integration of an inconsistent gradient field. Right: direct integration of a gradient field after inconsistency correction.

It is advantageous to apply the proposed method in all cases where color images have to be converted to grayscale for reproduction or for subsequent processing. The important benefit is that much more color features and contrasts are saved, see Figure 3.4, in comparison to usually applied conversion taking luminance values. Our experiments show that in comparison to existing approaches [Gooc05, Rasc05], the new method produces compelling results and it is much faster to compute.

3.5 Suggestions for Further Research

This section describes suggestions for further research on the topics discussed in the thesis.

Perceptual Evaluation of Image Quality Metrics

Besides the two evaluated approaches to the image quality assessment, several ad-hoc non-perceptual methods exist [Shei02, Marz02]. These methods are typically based on the assumption that we know the types of image distortions in advance. It would be interesting to inquire such methods in future evaluations. Moreover, it would be exciting to perform deeper study involving the *majority of approaches*

surveyed in the beginning of Chapter 3 of the thesis. Then, one could assess the bottlenecks and powerful features of individual image quality metrics as well as similarities and differences between them in a finer detail.

According to evident specific benefits of image quality assessment and HDR tone mapping (i.e. the mature methodology and numerous published approaches in the case of IQA, and a real-world dynamic range of luminances and modeling of advanced spatial visual phenomena in HDR tone mapping case), IQA and HDR tone mapping are naturally starting to overlap. Both IQA and tone mapping methods try to predict the appearance of an image (scene) to the observer. IQA methods then use this information to assess the quality of the input image, while TM methods use it for perceptual luminance range reduction. Originally, IQM models were strictly LDR, but these times are over now, notice e.g. an HDR version of the visible differences predictor [Mant05]. Furthermore, tone mapping method called iCAM [Kuan06a] is capable to model image appearance and to predict the differences as observed by subjects. It seems so that the modeling of *image appearance* that takes into account an HDR image as a whole is the common future of image quality assessment and HDR tone mapping. Sophisticated image appearance models could be utilized in a broad range of imaging applications, such as IQM, visual image difference, HDR TM, and prediction of visual phenomena.

Perceptual Evaluation of Tone Mapping Methods

The next question to answer in the evaluation of tone mapping methods using image attributes is how to *numerically assess the quality of reproduction of particular image attributes*. Although some approaches operating on LDR images were proposed in the literature [Jans01, Matk05], the HDR field deserves further investigation and perceptual verification. It is necessary to conduct consequential subjective experiments targeted on individual image attributes to be finally able to computationally assess the overall quality of images produced by tone mapping methods.

Furthermore, we are not aware of any experimental *evaluation of time-dependent tone mapping methods*. This is evidently harder task than the evaluation of tone mapping methods operating on static images (especially the testing with a real-world reference), however the results would be appreciated in many areas of imaging, including game and movie industry, interactive visualizations, HDR players, etc.

Hybrid Approach to Tone Mapping

Proposed hybrid approach to tone mapping can be *parametrized* instead of the current solution using luminance percentiles. Specifically, the construction of an enhancement map and the blending of local and global methods can easily be modified by user parameters. However, these parameters have to be carefully assessed in a subjective experiment, because it is of particular importance to preserve the perceptually plausible balance between the applied global and local methods.

The perception of images depends partially on the contents (semantics) of the image or the captured scene. Therefore every, even a subtle modification of an image can affect the quality of reproduction of an image attribute (in both positive and negative sense). In the future, we will conduct subjective perceptual experiments to uncover and quantify the *effect of particular local enhancement method* (in relation to the manner of enhancement map construction) *on the quality of reproduction of image attributes*.

Perceptually-Plausible Conversion of Color Images to Grayscale

In the future, we plan to further assess the performance of the proposed color to grayscale conversion algorithm, and we also intend to undertake more extensive experimentation, including *subjective testing on photographers and painters*, which is the input that we believe will lead to the best conversion. Moreover, we will explore a *multiscale solution* with the aim of making the method work in real time even for high resolution images.

An important and not really solved problem in color to grayscale conversions is an endorsement of the *temporal coherence*. When converting a color animation or series of color images sets (such as cartoons) into grayscale, several problems and possibilities arise: maintaining local consistence of gray levels between frames and/or global consistence throughout the animation, avoiding temporal artifacts, utilizing the temporal coherence for acceleration of the conversion, etc. Forthcoming method by Smith et al. [Smit08] applies global "absolute" mapping to overcome some of the mentioned issues. However the local adjustment which they subsequently apply may imply other existing problems.

As existing color to grayscale conversions operate on ordinary (LDR) images, another interesting improvement would be a perceptually plausible *direct conversion of HDR color images* to LDR grayscale images. Currently, one can solve this issue by applying a tone mapping method and a color to grayscale conversion successively. However, this approach may vanish important luminance and/or

chrominance details. Direct conversion of color HDR images to grayscale LDR images therefore potentially grants better results.

Finally, we are currently investigating how to utilize *optical illusions*, for instance the lightness illusions [Adel99], e.g. the simultaneous contrast effect for improvement of the grayscale rendition.

4 Conclusions

We concerned ourselves with image quality assessment metrics, high dynamic range tone mapping methods, and color to grayscale conversions in the thesis. In all these areas of digital imaging, exploiting the knowledge of the human visual system (HVS) and visual perception is particularly important. As methods we deal with usually involve a model of HVS, it is very advantageous and necessary to conduct experimental subjective analyses of these methods to validate and evaluate them properly. Besides exposing strengths and weaknesses of inquired methods, the experimental evaluations also attain a deeper knowledge of examined fields which can advance current state of the art and which can furthermore result in proposals of new approaches.

In the thesis, we presented and discussed the results of subjective experiment that we performed to compare and evaluate traditional error sensitivity based and structural similarity based approaches to the image quality assessment. Furthermore, we performed a study about the effects of basic image attributes for HDR tone mapping and surveyed how different methods reproduced these attributes. We proposed a scheme of relationships between essential image attributes, that led to the definition of an overall image quality measure. We presented and discussed the results of two different subjective psychophysical experiments that we performed to prove the proposed relationship scheme of image attributes. Moreover, we evaluated fourteen existing tone mapping methods with regard to these image attributes. We introduced a novel perceptually plausible, powerful hybrid approach to HDR tone mapping. The new approach is general and can be easily tailored to miscellaneous goals of tone mapping. Finally, we introduced the perceptually convincing local color to grayscale conversion technique based on the Coloroid color system and its extensive experimental background. As the method operated on gradient fields, we presented a new and efficient way of converting an inconsistent gradient field into a consistent one, which can be directly converted into an image by a simple 2D integration.

As we have shown, the utilization of human perception properties is profitable in various imaging applications, and finding novel unforeseen uses of HVS models in computer graphics and digital imaging is an interesting and valuable forthcoming work. To succeed, computer graphics researchers have to actively and closely communicate with vision scientists, psychologists, physiologists, and other researchers.

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Abstract

Computational approaches mimicking perceptual properties of the human visual system (HVS) have been successfully applied in various fields of computer graphics and digital imaging. The knowledge about the HVS is continually developing, however there are still many open questions and hypotheses. Naturally, we are far from having an accurate computational model of the HVS. It is therefore of particular importance and necessity to conduct experimental subjective analyses of the methods that incorporate HVS models to validate and evaluate them properly. Besides exposing strengths and weaknesses of inquired methods, the experimental evaluations on human subjects also attain a deeper knowledge of the examined field which can advance current state of the art and which can furthermore result in proposals of new approaches. The fields that traditionally utilize computational models of the HVS and which are concerned in this thesis are a) image quality assessment, b) high dynamic range tone mapping, and c) color image to grayscale conversions.

a) Image quality assessment metrics aim to predict the difference between images as perceived by human subjects. We present results of an experimental subjective evaluation of two principal approaches to image quality assessment (traditional error sensitivity based approach, and structural similarity based approach). The results show that the structural similarity outperforms the traditional approach for involved input stimuli.

b) The field of tone mapping has witnessed a lot of research effort to solve the problem of displaying images with high dynamic range (HDR) of luminance on ordinary output devices. We present a study about the effect of image attributes (contrast, brightness, etc.) in the HDR tone mapping. Furthermore, we present experimental subjective evaluations of global and local tone mapping approaches. Our results imply that proper global part of a tone mapping method is essential to obtain good perceptual results for typical real world scenes.

Motivated by implications of conducted studies, we propose a novel simple yet powerful general hybrid approach to tone mapping. In our approach, we apply a global tone mapping method first to reproduce overall image attributes correctly and we construct an enhancement map to guide a local operator to the critical areas that deserve an enhancement. The new approach is general and can be easily tailored to miscellaneous goals of tone mapping. An implementation of the proposed approach produces plausible results, it is easy to implement, and fast to compute.

c) Simple color image to grayscale conversions potentially disrupt chromatic informations contained in color images, and existing advanced conversions are eminently computationally intensive. We propose novel perceptually convincing local color to grayscale conversion techniques that operate in gradient domain. The novel methods produce perceptually justifiable results, and they have linear complexity in the number of pixels, which makes them suitable for high-resolution images.

Résumé

Metody napodobující vlastnosti lidského vizuálního systému (LVS) nacházejí široké uplatnění v řadě oblastí počítačové grafiky a digitálního zpracování obrazu. V samotném výzkumu vidění, z něhož tyto obory čerpají, však zůstává mnoho nezodpovězených otázek. Je tedy přirozené, že v současnosti není k dispozici přesný výpočetní model LVS. Mimořádný význam tak mají experimentální studie, ve kterých participují skuteční pozorovatelé. Takové studie jsou nepostradatelné pro validaci metod, jež využívají modely LVS. Nejen že výsledky těchto studií poukazují na silné a slabé stránky vyšetřovaných metod, ale zároveň prohlubují znalosti v dané oblasti. To může následně vést k návrhu nových, kvalitnějších a věrohodnějších výpočetních postupů. Podoblasti digitálního zpracování obrazu, jež tradičně těží z vědomostí o LVS, a kterými se zabývá tato disertační práce, jsou a) výpočetní odhady kvality obrázků, b) zpracování obrázků s vysokým dynamickým rozsahem jasů a c) převody barevných obrázků na šedotónové.

ad a) Výpočetní metriky kvality obrazu mají za cíl predikovat rozdíly mezi dvěma vstupními obrázky tak, jak by je vnímal reálný pozorovatel. V disertační práci jsou prezentovány výsledky experimentálního vyhodnocení dvou přístupů k této problematice (tradičních metrik modelujících LVS, a odhadů založených na strukturální podobnosti) na skutečných pozorovatelích. Výsledky studie ukazují, že metody založené na strukturální podobnosti předčí tradiční přístupy, ovšem ve specifické úloze (porovnání neuniformně komprimovaných obrázků) mají oba přístupy srovnatelné výsledky.

ad b) Kvalitní zobrazení obrázků s vysokým rozsahem jasů (HDR) na výstupním zařízení s omezeným rozsahem (LDR) je základním problémem výzkumu v oblasti zpracování HDR obrazu. K tomuto účelu bylo vyvinuto mnoho tzv. metod mapování tónů, jejich vzájemné výhody a nevýhody nejsou však doposud dostatečně prozkoumány. V disertační práci je prezentována studie základních atributů obrázků (kontrast, jas, atd.) a jejich významu pro mapování tónů. Dále jsou prezentovány výsledky experimentů, ve kterých byly vyhodnocovány publikované globální a lokální metody mapování tónů z hlediska věrnosti reprodukce reálné HDR scény. Výsledky ukazují, že percepčně korektní globální mapování tónů má zásadní vliv na kvalitu výsledku.

Na základě výsledků provedených experimentů je navržen nový hybridní přístup k problému mapování tónů. Při hybridním mapování tónů je nejprve aplikována globální metoda, která zajistí správnou reprodukci celkových rysů obrázku. Zároveň se konstruuje maska problematických oblastí obrázku, které jsou následně vylepšeny lokální metodou. Výběrem použitých metod a způsobem konstrukce masky lze dosáhnout různých cílů mapování tónů. Realizace hybridního přístupu produkují percepčně kvalitní výstupy, jsou výpočetně efektivní a implementačně jednoduché.

ad c) Převod barevného obrázku na šedotónový může v důsledku odstranění barevné informace vést k velmi neuspokojivým výsledkům. Existující pokročilé metody mají proto za cíl reprodukovat barevnou informaci stupněmi šedi, jsou však výpočetně velmi náročné. V disertační práci jsou navrženy rychlé techniky převodu, které pracují s gradienty vstupního obrázku. Nové metody produkují kvalitní šedotónové výsledky, mají lineární operační složitost a lze je tedy využít i k převodu obrázků s vysokým rozlišením.