Confidence in Tone Mapping Applying a User-Driven Operator

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ABSTRACT

In photorealistic image synthesis, the natural appearance of a scene is predicted by simulating the illumination using radiometric values. Whenever the dynamic range of the simulated luminance values exceeds the capabilities of the display device, tone reproduction is necessary to reduce the contrast of the image. Although a significant number of tone mapping operators have been presented in the past, the reliability of the resulting low dynamic range images cannot be guaranteed. In the context of product design, decision-makers rely on a trustworthy colorimetric and photometric appearance. We believe that in a particular scenario a dedicated user-driven tone reproduction curve outperforms existing operators in terms of flexibility, performance, and quality. In this paper, we propose a method to manually generate a tone mapping operator. The user is guided to select a set of simulated input luminance values and to map them to appropriate display luminance output quantities. These key mappings are interpolated to a tone mapping curve. A module was developed for Qtpfsgui to define and apply the operator. We evaluated the resulting low dynamic range images in a study with thirteen participants. The probands were asked to directly compare a real with a virtual scene displayed on a low dynamic range device as well as to rate the results in comparison to popular tone mapping operators. In addition to defining a dedicated curve for a specific scenario, another application of our approach is to generate a *standard observer* tone reproduction curve by interpolating a set of user-driven functions.

Keywords: tone mapping, image reproduction, high dynamic range (HDR), reliability, colorimetry, photometry.

1 INTRODUCTION

The aim of photorealistic computer graphics is to simulate virtual images by computing a set of radiometric measurements and to reproduce them exactly on the display device. The quality of both the simulation and the reproduction can be evaluated by comparing measurements of a real world scene with the respective measurements of the simulated and reproduced two-dimensional projection of the virtual scene on the display device. When the highest simulated luminance exceeds the maximum luminance of the output device, reproducibility is no longer possible. The same holds true for luminances below the black level of the display, respectively. One solution is to mark the luminance values, which are not reproducible, with false colors. In product design, a typical application field of photorealistic image synthesis, reliable rendering with natural appearance and colors is necessary. To display the simulated luminance values, the high dynamic range has to be reduced to fit the limited dynamic range of the output device.

In the past, a considerable number of popular tone mapping operators have been presented to address this issue. The key problem with all these approaches is to analyze to which extent the compressed image can be trusted. Especially in product design it is vital to create images decision-makers can rely on. In our opinion there is no single tone mapping operator to produce trustworthy results for each high dynamic range image and every presentation setup. In consequence, an expert in image processing needs to choose and validate a fitting operator for each setting and to adjust the individual parameters by hand. We strongly believe that it is more intuitive and less time-consuming to provide a highly flexible and interactive tool for the expert to create a dedicated tone reproduction curve for the given setting.

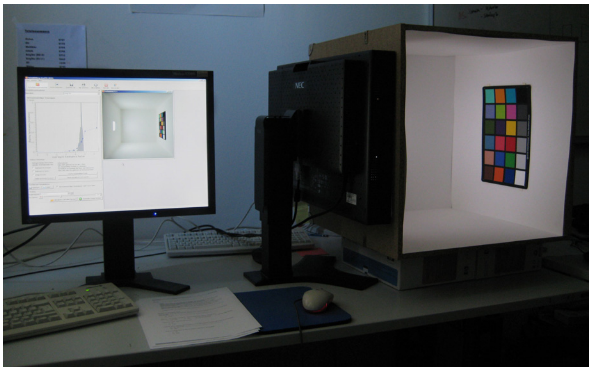


Figure 1: Setup of our direct comparison experiment

In this paper we present an approach of how to generate a user-driven tone reproduction curve. The user is guided to manually select a set of high dynamic input luminance values and map them to appropriate display luminances. These key mappings are interpolated to a tone mapping curve. An example module was developed for Qtpfsgui [12] to define and to apply the operator. Another key contribution is the evaluation of both our tool and the results of the user-generated curves in a study with thirteen participants. The reliability of the compressed images was validated by directly comparing a real with a corresponding virtual scene as well as by performing a benchmark test with established tone mapping operators. Furthermore, we generated a *standard observer* tone reproduction curve by interpolating all thirteen user-defined curves. This operator was applied to our test scenario and compared to popular tone mapping operators.

The remainder of the paper is organized as follows: Section 2 outlines previous approaches to the tone reproduction problem. Our solution is presented in section 3, while the evaluation setup is described in section 4. In section 5 we show the results of our evaluation and section 6 concludes this paper.

2 RELATED WORK

The challenge to reproduce real world scenarios with high contrast on media having limited capabilities can be traced back to painting more than five centuries ago. As justly emphasized by MacCann [11], the Renaissance artists were the first to capture realistic perspective and illumination in paintings using a restricted color palette. MacCann also pointed out that tone mapping has always been a challenging problem of photography because of the low dynamic range of print media. The importance of color reproduction in both photography and television is clarified in Hunt [8].

In computer graphics, the problem first arose when physically based images were created using ray tracing or radiosity. As opposed to scanline rendering with arbitrary RGB color values, global illumination algorithms tried to faithfully predict nature by simulating real radiometric values exceeding the dynamic range of the display devices. Tumblin and Rushmeier [16] realized this issue and presented a brightness-preserving operator as a solution in 1993. Operators aiming to preserve brightness or contrast are also subsumed to perceptual-match reproduction, whereon this paper is focused. An early representative of contrast-preserving tone mapping was introduced by Ward [17] in 1994, which reduced computational costs while sustaining just noticeable differences in contrast.

During the last years, a number of popular tone reproduction operators with diverse foci, inspired by fields as photography or the human visual system have been proposed. Reinhard et al. [14] adapted the photographic *zone system* to manually map the subjective middle-grey of the scene to an appropriate display luminance. The contrast can be enhanced locally with a technique inspired by photographic *dodging and burning*. Drago et al. [5] exploited the logarithmic response of the human visual system to incoming luminance. They showed how to handle a wide dynamic range by applying logarithmic compression with individual bases of the logarithm to different picture elements. Another operator, inspired by the response of human photoreceptors, was introduced by Reinhard and Devlin [13]. Based on electrophysiological studies, they designed a sigmoidal function to closely resemble the properties of the receptors. Comprehensive reviews of the most important operators can be found in the state of the art report by Devlin et al. [4] or in the textbook *High Dynamic Range Imaging* [15].

The diversity of approaches to tone mapping necessitates a systematic evaluation. Despite the problem of how to analyze the quality and reliability of tone mapping, a number of attempts are summarized in [19]. Relevantly to our work, Yoshida et al. [19] conducted a psychophysical experiment with 14 human observers. The probands had to compare a real world setting with an HDR photograph of the same scene, compressed and displayed on an LDR display. We chose to model a virtual representation of our well-defined real world scene and simulated a photometrically and colorimetrically consistent ground-truth image. Opposed to the HDR photography approach, our method eliminates inaccuracies from the camera calibration.

Another innovative strategy has been introduced by Mantiuk et al. [10], fitting a generic tone reproduction operator to an HDR image and its LDR counterpart, generated by an unknown existing tone mapping algorithm. They showed that a very simple and computationally inexpensive generic tone mapping curve is often able to reproduce indistinguishable results compared to the original complex algorithm. Furthermore, Mantiuk et al. demonstrated how to use their model to combine several popular operators to a new tone mapping curve. Similarly, we believe that a single tone mapping curve can outperform previously proposed operators in a dedicated scenario. But in contrast to choosing and combining operators by hand, we provide the expert user with a flexible tool to manually create the curve. In addition, we intentionally support no local contrast adjustment and do not change the chromaticities using saturation correction.

3 APPROACH

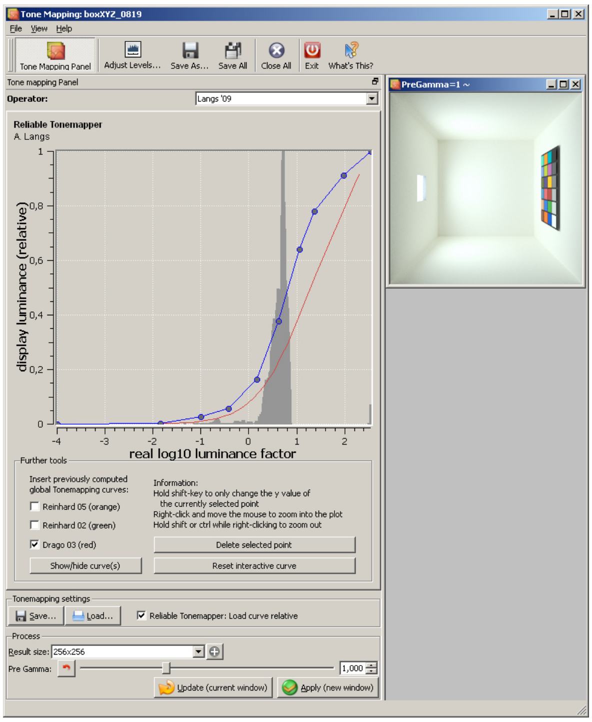
3.1 Criteria for reliability

The primary purpose of our tone mapping operator is to generate reliable output images. A reliable image should be indistinguishable from the respective real world scene for the human observer. In order to evaluate this goal we need to define criteria for reliability. Tone mapping operators aiming to create realistic results assess those criteria differently than operators trying to generate aesthetic images. Cadík et al. [3] proposed some important criteria: brightness, contrast, reproduction of color, reproduction of details and special attributes like artifacts. They say that the overall image quality, often also called naturalness, depends on several of those criteria. Furthermore, criteria which affect the image globally, such as contrast, are more important. Criteria like the local reproduction of details are of less importance. Cadík et al. conclude that global tone mapping methods are better suited for realistic images. Local tone mapping algorithms can only compete if they have a strong global part.

Yoshida et al. [19] pointed out that global tone mapping can preserve contrast better than local methods, but, on the other hand, local operators are better at reproducing details. They also deduce that no single criterion is solely accountable for the naturalness of the image. In our evaluation we use the criteria brightness, contrast, reproduction of details in shadows and in highlights, and the overall image quality.

3.2 Selecting tone mapping benchmarks

Similarly to both studies mentioned before, we aimed at conducting an evaluation with different tone mapping approaches. Hence, we considered a number of popular operators as potential benchmark algorithms and evaluated their ability to return a reliable LDR image. Global tone mapping operators like *Histogram Adjustment* by Ward [17], Drago's *Adaptive Logarithmic Mapping* [5] or the *Photoreceptor Model* by Reinhard and Devlin [13] are based mainly on the human visual system. Local tone mapping operators like *Photographic Tone Reproduction* by Reinhard et al. [14] or Ashikhmin's *Spatially Variant Operator* [1] have been considered as well. Operators working in the frequency or gradient domain are also popular, for example Durand's *Bilateral Filtering* [6] or *Gradient Domain Compression* by Fattal [7].



Operator: Langs '09

Insert previously computed global Tonemapping curves:

☐ Reinhard 05 (orange)

☐ Reinhard 02 (green)

☑ Drago 03 (red)

Information:
Hold shift-key to only change the y value of
the currently selected point
Right-click and move the mouse to zoom into the plot
Hold shift or ctrl while right-clicking to zoom out

☑ Reliable Tonemapper: Load curve relative

Result size: 256x256

Pre Gamma: 1,000

Figure 2: GUI of the interactive tone mapping tool

As a result we decided to use the Adaptive Logarithmic Mapping, Photoreceptor Model, and Photographic Tone Reproduction in our evaluation. Both frequency and gradient domain methods returned images which are better suited for aesthetical purposes. Drago's method has been chosen because it is very popular and a typical representative of the global operators. Reinhard's Photoreceptor Model benefits specifically from the fundamentals of the human visual system and separately computes a sigmoidal function on the three RGB channels corresponding to the three cone types on the retina of the human eye. At last, the Photographic Tone Reproduction represents a local tone mapping operator with a different approach, namely combining tone mapping with traditional methods used in photography. To summarize, we chose three very different operators, two global ones and a local one as benchmarks.

3.3 Implementation and features

The idea behind our tone mapping operator is to give an expert a tool at his disposal to create a specific tone mapping curve. Common image editing software like Adobe® Photoshop® provide tools to edit a gradation curve exactly. This well-known graph metaphor is exploited in our implementation to easily, rapidly and interactively adjust a tone mapping curve.

We used the open source software Qtpfsgui and the Qt Widgets for Technical Applications [1] to implement our curve tool. The main window, as seen in figure 2, shows a plot with the x-axis representing the real log_{10} luminance values and the y-axis representing

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[1] http://qwt.sourceforge.net

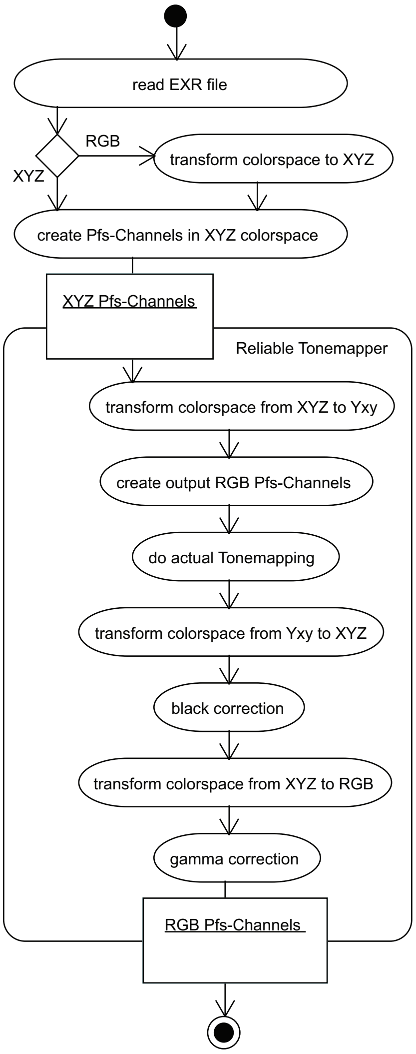

Figure 3: Activity diagram of the tone mapping pipeline

the relative display luminance. A display luminance of 1.0 corresponds to the maximum luminance of the display. The initial curve can be adjusted by setting or deleting control points. The curve is interpolated linearly between them. Holding the shift key restricts the movement of the point to the y-direction in order to avoid shifting the point and therefore changing a different input luminance value.

Additionally, luminance quantities in the image can be mapped precisely to a control point in the plot at the corresponding luminance value. A simple click inside the image creates the correct control point which can be further adjusted. For better comparison, it is possible to import tone mapping functions created by the operators from Drago and Reinhard. Furthermore, user-driven curves can be saved to or loaded from disc. Hence, those curves can be applied to arbitrary images by loading the control points absolutely or relatively. The former method loads the points at the absolute input luminance values regardless of their existence in the new image. The latter option stretches or squeezes the points relatively to the new luminance range.

Another important aspect of our approach to tone mapping is the photometrically and colorimetrically consistent implementation in order to evaluate correctly later on. Figure 3 illustrates the pipeline a high dynamic range OpenEXR file [2] has to pass before being displayed: Three channels in the CIE XYZ color space are created from the OpenEXR file. Those channels are transferred to the actual tone mapping algorithm which transforms the color space to Yxy. The plot curve is evaluated for every luminance value in the image, returning the value on the y-axis between 0.0 and 1.0 at the x-position of the requested input luminance. Only the luminance channel Y is changed by multiplying the looked-up y-value with the maximum display luminance. The display was measured with an X-Rite i1-pro spectroradiometer and the i1 Share software beforehand and the generated ICC profile was activated for gamma calibration. After the plot look-up process the color space is transformed back to XYZ and a black correction is executed. Then the color space is further transformed to RGB using the measured color primaries of the specific display. Finally, gamma correction is applied.

4 EVALUATION

4.1 Scenarios

To validate the reliability of our user-driven tone mapping operator, we conducted a relative comparison to the selected benchmark operators from section 3.2. Therefore, we generated an HDR photograph using exposure bracketing with a Canon EOS D30 digital reflex camera of a scene on our campus. The HDR image has been calibrated with a Kodak CS100A luminance measurement device and created by webHDR [3]. The campus scene is depicted on the left in figure 4.

Besides this relative comparison, we conducted a direct comparison between a real world scene and a simulation of the same scene, displayed on a low dynamic range device. We constructed a well-defined real world scene and modeled an exact virtual representation. A ground-truth simulation of the virtual scene was computed with path tracing using a spectral ray tracing system and measured radiometric input values for the light source and the materials. The simulated two-dimensional projection was displayed on a colorimetrically characterized and gamma-corrected device. In figure 1, a photograph of the setup is shown.

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[2] http://www.openexr.com/

[3] http://luxal.dachary.org/webhdr/

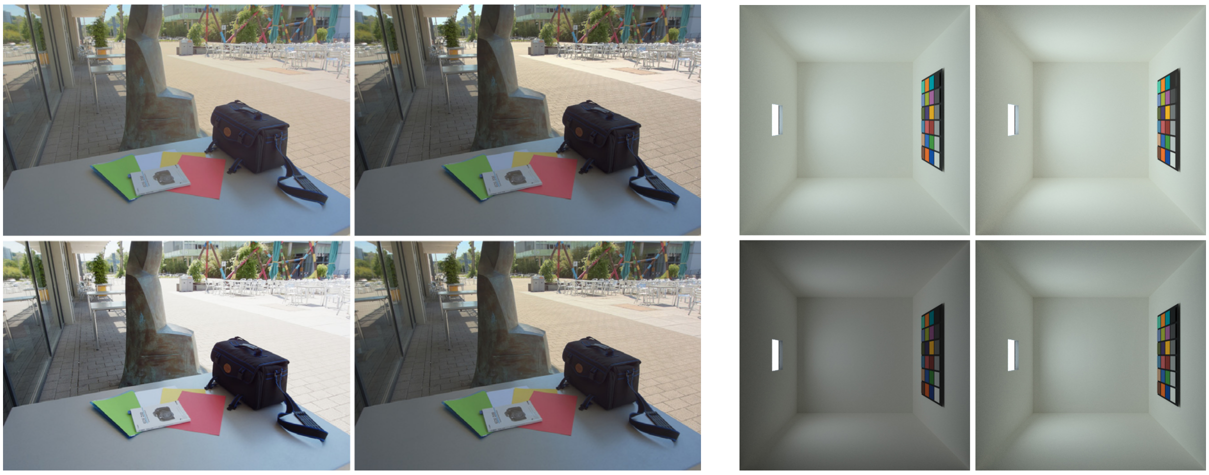

Figure 4: Campus scene (left hand side) and the well-defined box scene (right hand side), each reproduced with Drago's Adaptive Logarithmic Mapping (top left), Interactive tone mapping (top right), Reinhard and Devlin's Photoreceptor Model (bottom left), and Reinhard's Photographic Tone Reproduction (bottom right)

The box measures $0.5m$ in all three dimensions. The front side is left open for the observer. In the center of the left side a square hole with $0.1m$ edge length is spared for a calibrated NEC SpectraView 2690 as the light source. On the right, opposing the light, a Munsell ColorChecker chart was placed. The remainder of the interior of the box was wallpapered with a diffuse white Canson Mi-Teintes Paper. The spectral distributed radiance of the light source and the spectral distributed reflectance of the materials were measured with an X-Rite i1-pro spectroradiometer. An exact virtual representation of this box was modeled. We generated a ground-truth simulation using spectral path tracing. An EIZO FlexScan S2000 displayed the synthetic image using color calibration and black correction. The simulation was validated for low dynamic range images by comparing measurements of the display device with measurements in the box to grant trustworthy results. For our experiment, the light source was calibrated to the maximum luminance of $300cd/m^{-2}$ and the display device to $100cd/m^{-2}$. The box scenario is displayed on the right in figure 4.

4.2 User study

We believe that an individually created tone reproduction curve excels every other tone mapping operator in a specific scenario. We wanted to evaluate whether tone mapping curves created by our probands really deliver a good result measured by the former mentioned criteria and if there are concurrences between those curves and curves of popular tone mapping operators. We approached the question whether the users created similar curves or if there is even a kind of *standard observer* tone mapping curve. Finally, we checked how the users rated the usability of the curve tool.

Thirteen participants aged 21 to 30 years created curves and evaluated the resulting images. During the whole evaluation process we were present to help in case of operating problems or questions. The main functions and keyboard shortcuts of the interactive tool were explained. We pointed out key areas in the images to support the test persons when evaluating the reliability criteria. In a first step, all thirteen participants were asked to fill out a general questionary. Level of knowledge, experience with HDR software and existence of color deficiencies were some of the questions. One half of the test persons had some experience with other HDR software.

The first experiment was a relative comparison of the campus scene without direct reference. All participants had to rate four pictures displayed on an LDR device according to the criteria introduced in section 3.1. The setting of the Adaptive Logarithmic Mapping, Photoreceptor Model and Photographic Tone Reproduction were set to the default values proposed in their respective papers, with the following exceptions: the sharpening parameter of the Photographic Tone Reproduction was set to 1.6. The intensity parameter of the Photoreceptor Model was set to -3, the chromatic adaptation to 1.0, and the light adaptation to 0.0. We created our dedicated tone mapping curve for the interactive tone mapping without direct reference. The probands were asked to rate the criteria on a scale with five discrete steps, from *too few/low* to *too many/high* and a possibility to rate *accurate*.

In the second experiment the probands had to create their own tone mapping curve for the aforementioned box scene. The first request was to ensure that the grayscale of the colorchecker was reproduced correctly on the screen. Then they adjusted the color patches

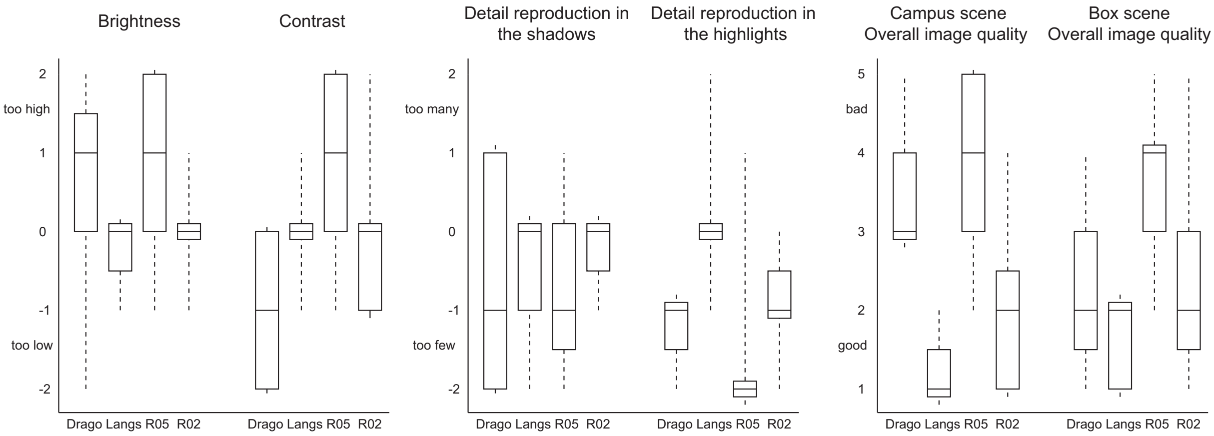

Figure 5: Tone mapping criteria evaluation. The operators are labeled as Drago2003 (Drago), Interactive Tonemapping (Langs), Reinhard2005 (R05), and Reinhard2002 (R02): the box shows the lower quartile, median, and upper quartile values. The dashed lines (whiskers) extend from the maximum to the minimum values of the datasets

and the box itself. In addition, the test persons were asked to rate the usability of the tone mapping interface and the time needed to create a curve. The last task was to compare the result of the own curve applied to the box scene with the results of the selected popular tone mapping methods. A grade was requested for the overall quality of each result.

5 RESULTS

5.1 Campus scene

The first criterion to be evaluated was the brightness of each image. Reinhard's Photographic Tone Reproduction (henceforth referred to as Reinhard02) was rated best, followed closely by the curve created with the interactive tone mapping approach. Both results from Drago's Adaptive Logarithmic Mapping (Drago03) and Reinhard and Devlin's Photoreceptor Model (Reinhard05) were rated too bright, probably because the bag and chair areas were not displayed bright or dark enough. The contrast was reproduced best by the interactive tone mapping operator. Reinhard02 created the second best contrast tending towards too little contrast. Again, the results of Drago03 and Reinhard05 were not satisfying. Reproduction of detail in the shadows was solved best by Reinhard02, followed by the interactive curve. The grades of the test persons for Drago03 were very scattered but tended to have too few details. Reinhard05 did not deliver sufficient details in the shadows. Details in highlights were preserved best by the interactive operator. All the other tone mapping algorithms retained too few details, according to our test persons. To summarize, Reinhard02 and the interactive operator performed equally well. Both the Drago03 and Reinhard05 tone mapping could not compete in our first scenario.

This observation is supported by the grades given for the overall image quality. If we can assume, that the grades are interval data, the interactive operator received the average grade 1.2, Reinhard02 2.0, Drago03 3.5, and Reinhard05 3.9 where 1 is very good and 5 is very bad. The Box-Whisker-Plots in figure 5 show all obtained data with median, upper and lower quartile and maximum plus minimum values. Anyhow, we can conclude that not a single criterion is important for the overall image quality because otherwise the grades for the interactive tone mapping operator and Reinhard02 grades would not differ so much. An expert curve seems to provide the best overall image quality, but needs to be created carefully beforehand for each scene.

5.2 Box scene

Fourteen curves have been created for the box scene over the course of the evaluation, one of which we created ourselves as a kind of expert curve. The created curves are very different because the emphasis has been set differently by the users: some only tried to map the greyscale correctly; others mapped all colors on the colorchecker precisely. Because of the latter outlier points have been inserted making the resulting curve bumpy and not monotonically increasing. This results in some artifacts and those points have therefore been erased from the dataset after the evaluation. In figure 6 those normalized curves are depicted. In this context, we thought of a standard observer curve averaged over all curves. This curve is shown in figure 6 on the right hand side. The standard observer curve matches the Drago03 curve for the box scene in a wide range of input luminance values. Reinhard02's curve for this scene has a similar shape. This might be caused by the box scene since the dynamic range ($\approx$ 300:1) is close to the dynamic range of the display ($\approx$100:1).

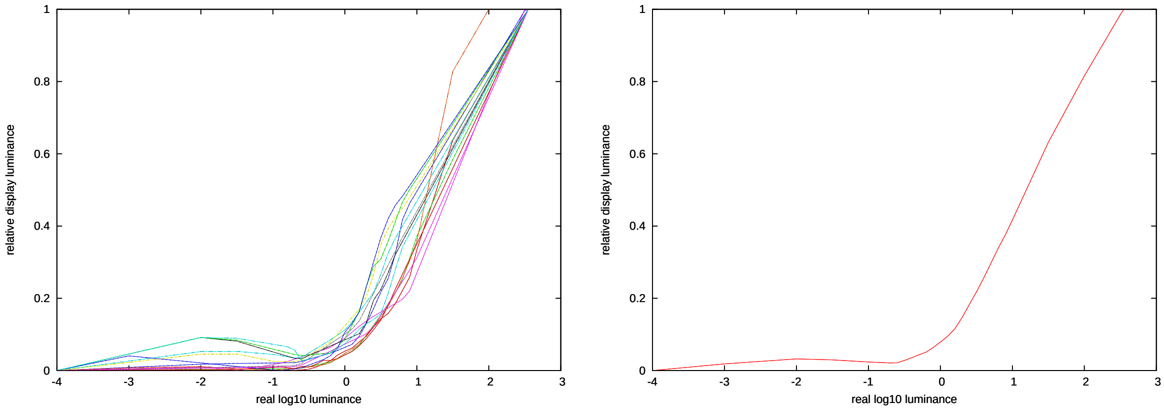

Figure 6: Tone mapping curves of the test persons (left hand side) and the standard observer curve (right hand side)

The participants needed between 5 and 24 control points with an average of 13 to create a satisfying curve. The linear interpolation seems to suffice for a reliable result. The probands required 15 minutes on average to generate their curves, which was overall rated as an acceptable time frame. Also, the users were pleased with the usability of the curve tool. After a short orientation time every participant was able to create a curve with an outcome they found acceptable.

At last, another grade for overall image quality has been given for the results of the individual curve and the other three benchmark operators. On average, the users were very confident with their individual LDR image (average grade 1.7) followed by the results of Drago03 and Reinhard02 (2.3 and 2.4, respectively) and Reinhard05 (3.8). This is not surprising since we already concluded that the first three mentioned tone mapping curves are quite similar. Still, a specifically created curve for a single selected scene yielded the best perceived overall quality.

5.3 Comparison to other evaluations

Kuang et al. [9] compared six tone mapping algorithms in their study, two global and four local ones. They used HDR images without reference and some invariant constructed scenes for a direct comparison. None of the tone mapping operators performed well for every image. Thus it is reasoned that there is a significant dependency between the tone reproduction method and the selected scenario. The Photographic Tone Reproduction and the *Bilateral Fast Filter* by Durand et al. [6], two of the four local operators, performed best on average. Both global operators, the *Sigmoid Transformation* [2] and Histogram Adjustment [18], did not achieve good results overall.

Another work from Yoshida et al. [19] examined seven tone mapping operators in direct comparison. Several criteria had to be rated by the participants. Most importantly they found out that global operators achieved a higher contrast whereas local operators retain details better. No single criterion was deemed to exclusively contribute to the overall image quality. The results of the Photographic Tone Reproduction, Histogram Adjustment and Adaptive Logarithmic Mapping [5] were rated best in the overall image quality, the last two mentioned being global operators.

In fact, Cadíks et al. suggest in their evaluation [3] with fourteen tone mapping methods that global operators perform better in terms of overall image quality. Local ones can only compete if they have a proper global part. Criteria, which apply to the whole image, like contrast, are most important for the overall quality. According to [3], this is why global operators exhibit better results. An example of a good local operator with a strong global part is the Photographic Tone Reproduction once more.

Comparing those observations with our results yields some conformity: Photographic Tone Reproduction produces good results in every evaluation including ours. Because our interactive tone mapping operator even exceeds the results of the Reinhard02 operator, it might be quite possible for our results to be reproduced under different conditions, although accompanied by a lot of work due to the need of a separate curve for every scene. The global approach of our tone mapping method can be reassured by the results of studies revealing that a global tone mapping operator delivers a better perceived overall image quality. A reliable result for every scene was the goal of our implementation and can be obtained by creating an individual curve.

6 CONCLUSION AND FUTURE WORK

In this paper, we proposed to apply an interactive and highly adjustable user-driven tone mapping function as a dedicated tone reproduction operator for individual high dynamic range scenarios and specific presentation setups. This operator was designed and developed for industrial product design as main field of application, where decision-makers rely on trustworthy colorimetric and photometric lighting simulation and reproduction. The expert user is guided by our tool to define and to apply a set of key mappings between the scene luminance values and low dynamic range display quantities. These two-dimensional control points are interpolated to a tone reproduction curve that can be stored, loaded or compared to other tone mapping curves.

To validate our approach, we chose criteria for reliability and popular tone mapping operators as benchmarks. A user study with thirteen participants and two very different scenarios was conducted. The first experiment was based on a relative comparison of a user-defined expert curve and existing tone mapping operators from literature without direct reference. In the second experiment, the test persons were asked to generate their own tone reproduction curves in a scenario with direct reference to a well-defined real world setup and to compare the resulting display images with other published operators. Our findings include that the probands were able to create satisfying operators with a small number of thirteen key mappings in an acceptable time frame of fifteen minutes on average. The users rated the reliability of the individual curves higher than the results of existing tone mapping operators. Finally, we presented a standard observer tone mapping curve, generated by averaging the results of a number of test persons for an individual scene and presentation setup.

We expect interesting results from future work on evaluating similarities within groups of standard observer operators from different sets of scenes and presentation setups. Another future application of our approach is to generate the tone mapping curve using existing operators from literature and to use our tool for manual fine tuning. Lastly, we are looking forward to the results of evaluating our user-driven tone mapping operators in an industrial product design environment, where our tool was designed for.

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