Perception-Based Contrast Enhancement Model for Complex Images in High Dynamic Range

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ABSTRACT

Contrast in image processing is typically scaled using a power function (gamma) where its exponent specifies the amount of the physical contrast change. While the exponent is normally constant for the whole image, we observe that such scaling leads to perceptual nonuniformity in the context of high dynamic range (HDR) images. This effect is mostly due to lower contrast sensitivity of the human eyes for the low luminance levels. Such levels can be reproduced by an HDR display while they can not be reproduced by standard display technology. We conduct two perceptual experiments on a complex image: *contrast scaling* and *contrast discrimination threshold*, and we derive a model which relates changes of physical and perceived contrasts at different luminance levels. We use the model to adjust the exponent value such that we obtain better perceptual uniformity of global and local contrast scaling in complex images.

1. INTRODUCTION

In the recent years, we witness significant progress in the display technology in terms of expanded color gamut, luminance dynamic range, and physical contrast. For example, specialized high dynamic range (HDR) displays[1] can reproduce luminance levels ranging from 0.015 to 3,000 cd/m^2, but even modern LCD TV sets feature remarkable luminance ranges of 0.1–800 cd/m^2. This results in much better visibility of details in deep shadows and bright highlights; it makes the reproduced images more plausible with respect to the real-world observation conditions. In particular, the black level in such displays guarantees that the darkest image regions appear black in contrast to the grey appearance of such regions on older displays with the minimum luminance higher than 2–5 cd/m^2.

The dynamic range and contrast expansion of display devices require revisiting well-established image processing techniques which are often tailored for 8-bit color depths and luminance ranges typical for the once prevailing CRT displays. For example, image contrast manipulation is often based on the assumption of contrast constancy, i.e. invariance of perceived contrast over variations of display dynamic range. Peli et al.[2] investigated the contrast constancy problem for various luminance adaptation values and simple stimuli such as the Gabor patches imposed on background with different mean luminance. In two independent contrast matching and contrast magnitude estimation studies, they confirmed that contrast sensitivity is significantly reduced for low luminance adaptation values below 3–8 cd/m^2. The lower the physical contrast of the Gabor patches, the stronger the sensitivity reduction observed, with a typical contrast versus intensity (cvi) characteristic observed for near threshold contrast values. Effectively, this means that, on modern displays, simple contrast rescaling may lead to image distortions manifesting in changing apparent contrast relations with respect to the original image through weakening perceived contrast in dark image regions. In this work, we consider this problem in the context of complex images and for luminance ranges typical for HDR displays. Our goal is to derive a model relating physical and apparent contrast, which can be applied to improve visual uniformity of contrast changes resulting from image contrast manipulation.

We investigate the standard equation for contrast scaling in image processing:[3]

$$L(c) = \bar{L}\left(\frac{L}{\bar{L}}\right)^{c} \tag{1}$$

where L denotes the luminance of a pixel, $\bar{L}$ is a luminance reference, and c denotes the *contrast factor*. The luminance reference $\bar{L}$ defines the brightness level which remains unchanged during contrast scaling and usually equals the minimum or maximum luminance in an image, what gives normalized base in Equation (1). To test the perception of contrast scaling in areas of different luminance, we set the $\bar{L}$ value to the mean luminance in the analyzed area. The *contrast factor* defines physical change to contrast in such a sense that a value of $c = 2$ increases while $c = 1/2$ decreases the physical contrast twice. Furthermore, the *contrast factor* is a relative measure of contrast which is convenient to use and interpret within the scope of presented applications. It also allows to analyze the contrast change in terms of one number without measuring actual contrasts, which is particularly important since a single number physical contrast measure for complex images is difficult to be quantized.

The goal of our research is to parameterize c in such a way, that a specified contrast change is perceived as a uniform modification of the image independently of luminance levels and contrasts existing in the given local area. Furthermore, we apply the parameterized model for arbitrary images in order to generate a contrast-enhanced version of them. We first conduct perceptual experiments to establish the relation between physical and apparent contrast changes in a complex image (Section 2), and derive a model encapsulating this relation in Section 3. We discuss the observed relations in Section 4 and in Section 5 propose a method for perceptually uniform contrast scaling in images displayed over high dynamic range. We conclude the paper and outline future work in Section 6.

2. PERCEPTUAL EXPERIMENTS

We conducted two psychophysical experiments, a *contrast scaling* and a *contrast discrimination threshold* tasks, to assess how the human visual system (HVS) perceives physical contrast changes. The goal of the *contrast scaling* experiment is to obtain uniform scalings of perceived contrast for the human observers with respect to given physical contrast for various luminance adaptation conditions. In this experiment, we employed a two-alternative forced choice (2AFC) procedure for image pairs with different *contrast factors* and the same luminance levels and analyzed the obtained data using Thurstone's Law of Comparative Judgment for *contrast scaling* experiment.[4]

Thurstone's Law of Comparative Judgment gives arbitrary uniform scaling for each set of stimuli at different luminance levels. We can compare distances between stimuli, i.e., perceived contrast magnitude, within the same set but cannot compare different sets of stimuli to each other. For rescaling the results of Thurstone's scaling to a contrast space compatible for all stimuli sets, a *contrast discrimination threshold* experiment was conducted using the Parameter Estimation by Sequential Testing (PEST) procedure.[5] In this experiment, each subject was shown pairs of stimuli. One pair of stimuli contains reference and target images shown one after another randomly, and we asked a subject to report if they saw any difference between given two images. The details for both experiments are described in Sections 2.2 and 2.3.

2.1 Stimuli and Apparatus

We selected a black-and-white image of the resolution 900×600 (see Figure 1). This is a typical landscape image with luminance and contrast patterns which we can observe in natural images. This image was segmented based on luminance levels into three different regions: "dark", "medium", and "bright" and our experiments were conducted on two displays: the Westinghouse high resolution digital television (HDTV) and the BrightSide DR37-P HDR display.[1] We used the Westinghouse display, one of the commercial liquid crystal displays (LCDs), because it has better uniformity of its back-light but obviously can not reproduce very low luminance levels. Therefore, we also employed the BrightSide HDR display which makes it possible to reproduce very low luminance levels by spatially varying light-emitting diode (LED)-based dimming technology. Both displays use the same LCD sandwich type and were carefully calibrated by measuring its luminance response for a range of input values using the MINOLTA LS-100 light meter. Except their reproducible dynamic ranges, both displays have similar characteristic.

In order to reproduce very low luminance level, we uniformly reduced the power of LED back-lights of the BrightSide HDR display, and the former "dark" became "very dark" region. The mean luminance levels are 0.3, 4.5, 28.8, and 158.5 cd/m^2 for "very dark", "dark", "medium", and "bright" areas, respectively.

Each display was placed approximately 1.5 times of its diagonal size away from a participant and viewed binocularly for both experiments. All experimental sessions were conducted in a room whose lighting condition is fully controllable and under dim illumination (65 lux).

2.2 Experiment 1: Contrast Scaling

Contrast scaling experiment was conducted for estimating perceived contrast at physical contrast change at different luminance levels. We employed a 2AFC analyzed by Thurstone's Law of Comparative Judgment[4] which are commonly used for measuring distances between stimuli in uniform continuous scaling.

(a) “Very dark” and “dark”. (b) “Medium”. (c) “Bright”.

Figure 1: *Our test image (top) and its masks (Bottom). The average luminance levels are 0.3, 4.5, 28.8, and 158.5 cd/m^2 for “very dark”, “dark”, “medium”, and “bright” regions respectively.*

In each trial of *contrast scaling* experiment, a pair of stimuli was displayed next to each other randomly and the region of interest was specified through colored contours (see Figure 2). In each stimulus, a different *contrast factor* has been applied only to the selected image region. The other regions in an image are present but slightly blurred (Gaussian blur, $\sigma = 10$) not only to maintain similar local luminance adaptation in an image but also to reduce subjects distraction to non-selected areas. Subjects were asked to switch the contour off and judge in which image they were able to see more contrast in the specified areas. Every participant took approximately 20 – 30 minutes to complete this experiment. The results of Thurstone’s scaling are shown in Figure 3 and Table 1.

Before the main part of the experiment, we conducted a pilot study to prepare a set of stimuli so that contrast differences are right below the visibility threshold. We prepared several different sets of stimuli in the form of $c = 1.11^n$, $c = 1.13^n$, and $c = 1.15^n$ where $n = -5, -4, \ldots, 5$ and selected $c = 1.13^n$. Since 2AFC increases the number of trials extremely, we used only one image for our experiments. Although we used only one image for our experiments, we still had 220 pairs to compare, which is too many to judge for subjects. Therefore, we removed 68 obvious pairs and conducted the experiments comparing 152 pairs (see[6] for details how to reduce experimental labor).

11 subjects between 28 – 47 years old (31 in average) participated in this experiment. Four of them were female and the rest were male. Every participant reported normal or corrected to normal vision, and everybody was naïve for the goal of the experiment.

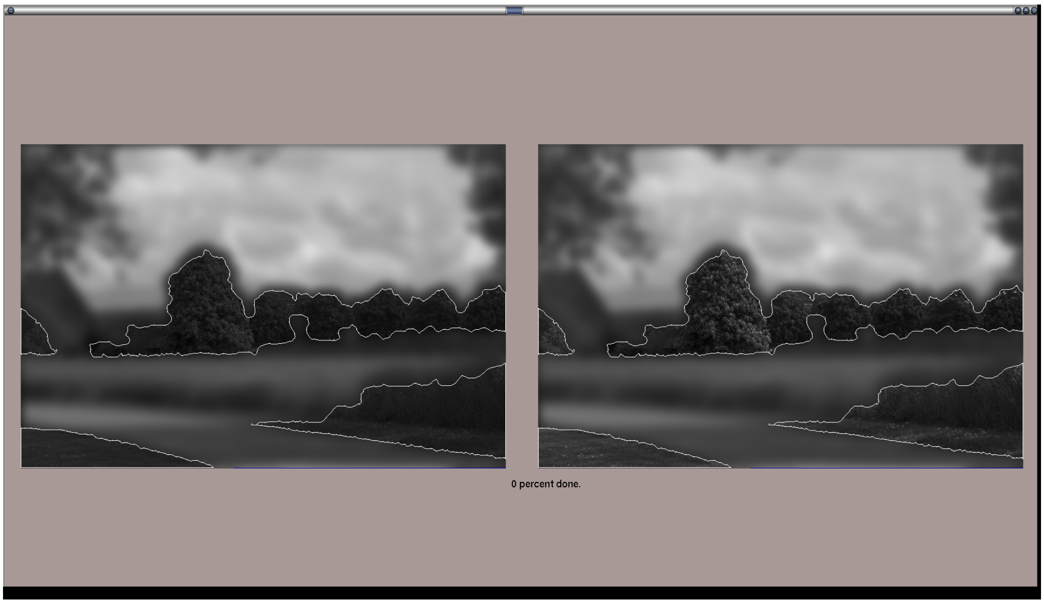


Figure 2: *A screenshot of contrast scaling experiment. The selected areas are surrounded by colored contours to let a subject know to which areas they have to pay attention. The rest of an image is blurred to reduce a subject's distraction and to maintain luminance local adaptation.*

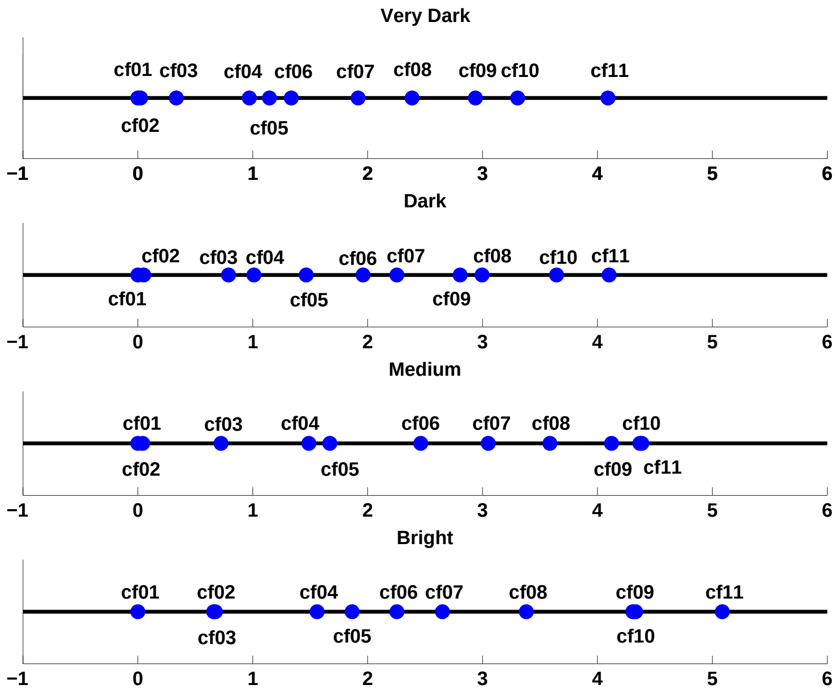


Figure 3: *Results of contrast scaling experiment analyzed by Thurstone's Law of Comparative Judgment. The labels* $cf01, \ldots, cf11$ *denote the contrast factors ordered from the smallest to the biggest values (see Table 1 for the details). Note that we can not compare them directly to each other because they are given in arbitrary units. We have to rescale them to JNDs by using the results of* contrast discrimination threshold *experiment (see Section 3).*

Labels in Figure 3	cf01	cf02	cf03	cf04	cf05	cf06	cf07	cf08	cf09	cf10	cf11
Contrast factors	0.54	0.61	0.69	0.78	0.89	1.00	1.13	1.28	1.44	1.63	1.84
Very dark	0	0.02	0.33	0.97	1.15	1.34	1.92	2.39	2.94	3.31	4.09
Dark	0	0.05	0.79	1.01	1.47	1.96	2.25	2.99	2.80	3.64	4.10
Medium	0	0.04	0.72	1.48	1.67	2.46	3.04	3.58	4.12	4.36	4.38
Bright	0	0.66	0.67	1.55	1.86	2.25	2.65	3.38	4.30	4.33	5.08

Table 1: *Results of contrast scaling experiment analyzed by Thurstone's Law of Comparative Judgment. The labels for contrast factors correspond to those in Figure 3.*

2.3 Experiment 2: Contrast Discrimination Threshold

Another subjective experiment was conducted for measuring *contrast discrimination thresholds* so that we can rescale the results of *contrast scaling* experiment from arbitrary units to just noticeable difference (JND) unit. We employed the Parameter Estimation by Sequential Testing (PEST)[5] at three reference points of *contrast factors* ($c = 0.69, 1.00, 1.44$) for all four regions. At each reference contrast, its target contrast was started at significantly different point. One of the reference and target images was shown with colored contour surrounding the selected areas, the contour disappeared, and then another image was shown. A subject was allowed to repeat displaying each trial as many times as they wanted. In this experiment, the task of a subject was to report if there was visible difference between two images in a specified region. One trial was ended when the recent five thresholds were constant enough; i.e, a trial finished if the standard deviation of the recent five thresholds was below 0.05.

Six people participated in the *discrimination threshold* experiment, which took 20–30 minutes for each subject. Everybody had participated in the *contrast scaling* experiment first, because we were interested in measuring *contrast discrimination threshold* for the same series of images as for the *contrast scaling* experiment. The results of the *discrimination threshold* experiment for contrast increments are shown in Table 2. Inter-observer variability was tested by one-way analysis of variance (ANOVA) before calculating *contrast discrimination threshold* in order to remove outliers. There were a few cases with outliers, but after removing them, all p-values are much higher than the significant level (0.05), i.e., they statistically behaved in the same way.

Reference *contrast factors*	$c = 0.69$	$c = 1.00$	$c = 1.44$
Very dark	0.14	0.14	0.16
Dark	0.09	0.09	0.07
Medium	0.07	0.07	0.07
Bright	0.09	0.08	0.10

Table 2: *Contrast discrimination thresholds* Δc *at three reference contrast factors as measured for contrast increments.*

3. MODEL

In this section, we derive a model which adjusts the *contrast factor* for a desired perceptual contrast change as a function of luminance level. The results of *contrast scaling* experiment (Figure 3) are rescaled to just noticeable difference (JND) units by using the results of *contrast discrimination threshold* experiment (Table 2) using the following procedure:

1. Setting the origins to the *contrast detection thresholds* computed by *contrast sensitivity function* for each luminance level.

2. Rescaling the outcome of the *contrast scaling* experiment to match the result of the *contrast discrimination threshold* experiment. The distance between reference contrast and the threshold obtained by the *contrast discrimination threshold* experiment is considered as 1 JND.

3. Fitting the points obtained in Step 2 to power functions. Note that every point is rescaled in *absolute* JND units now. For practical use, we simply change the *absolute* JNDs to *relative* JNDs by setting the point of "medium" curve at $c = 1.0$ to 0 JND for *relative perceived contrast* (see Figure 4). The coefficients of the power function $\alpha c^{\beta} + \gamma$, where c is the *contrast factor* for each luminance level, are given in Table 3. All R-square values of power fittings are above 0.93 for our data.

4. Interpolating the curves in Figure 4 to construct a surface model with parameters of mean luminance level, *contrast factor*, and relative perceived contrast in JND units (see Figure 5). Cubic interpolation is employed.

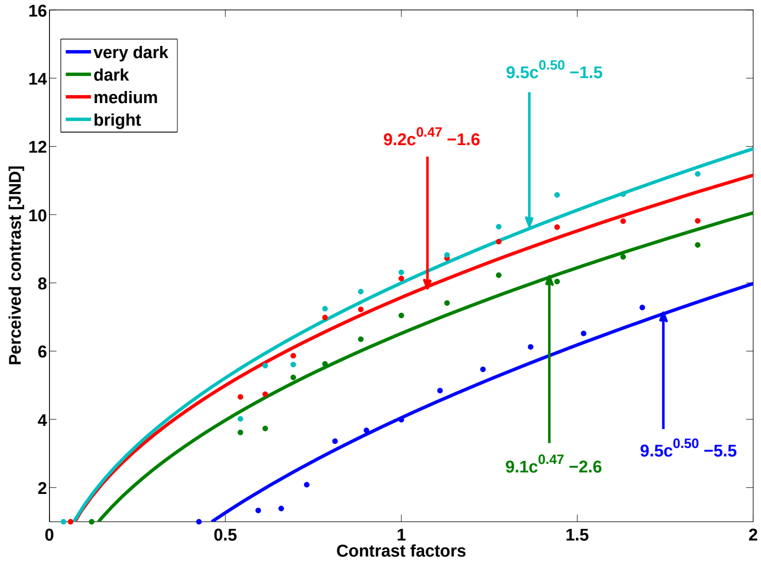


Figure 4: *Relative perceived contrast in JNDs at different luminance levels for given contrast factors. Dots represent the rescaled data for each corresponding image region. Coefficients of each curve are shown in Table 3.*

	α	β	γ
Very dark	9.50	0.45	-5.5
Dark	9.09	0.47	-2.6
Medium	9.21	0.47	-1.6
Highlight	9.50	0.50	-1.5

Table 3: *Coefficients for the power function $\alpha c^{\beta} + \gamma$ in Section 3 for measured luminance levels. See also the plots in Figure 4.*

After all steps shown above, we derive the following formula for relative perceived contrast C_p:

$$C_p(c, L) = 9.3c^{0.47} + \gamma(L) \tag{2}$$

where c is given *contrast factor* and L is the logarithm of mean luminance of a segmented region. The values of α and β are computed as average values in Table 3. The $\gamma(L)$ coefficient part is derived as

$$\gamma(L) = \frac{0.31L - 6.1}{L + 1.7} \tag{3}$$

by fitting to a rational function with R-square 0.99. Figure 5 visualizes this model.

4. DISCUSSION

The studies of physical versus perceived contrast change in the context of simple patch stimuli or sinusoidal patterns have led to the derivation of *power law* for contrast discrimination[7–9] and *contrast transducer* functions.[10,11] Although it is yet unclear how to objectively compare these findings to our studies on a complex image, we analyze and discuss apparent similarities in the following sections. Throughout the analysis we refer to the *contrast factor* c as a relative contrast measure, therefore both thresholds and scaling are expressed in it.

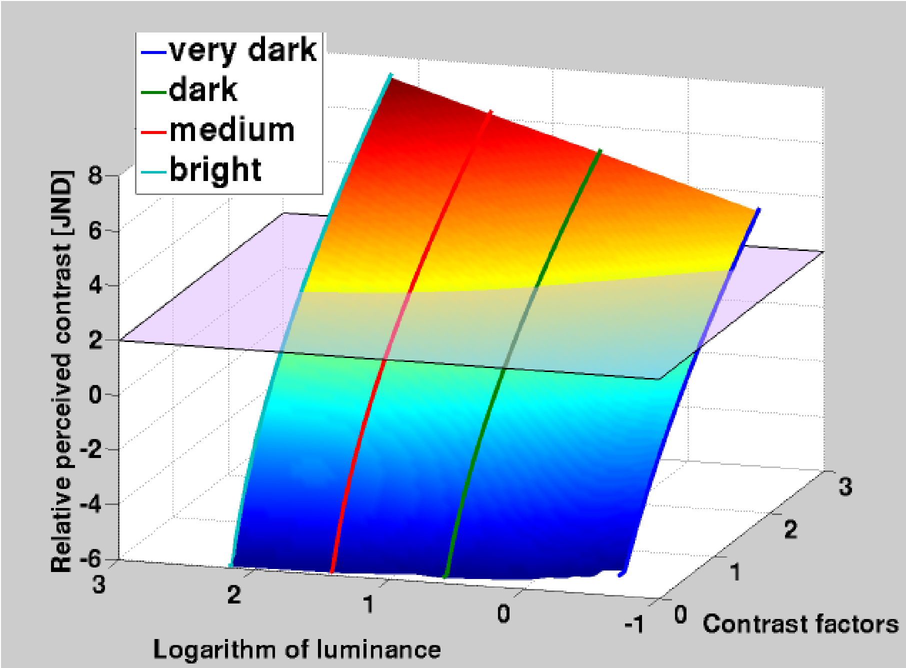


Figure 5: *A surface model of perceived contrast in JNDs with respect to different mean luminance levels and contrast factors (see Equation* (2)*). A transparent surface shows that we need different contrast factors for different luminance levels to achieve the same perceived contrast (8 JNDs as an example). The curves derived in Figure 4 are also displayed on the surface.*

4.1 Supra-threshold Contrast Discrimination

According to the data in Table 2, contrast discrimination threshold remains approximately constant for different *contrast factors* and has consistent characteristic across the luminance changes. While *contrast factor* is a measure relative to the existing contrast in the area, it means that we observe a contrast masking effect[12] with exponent close to 1. The discrimination threshold for *contrast factor* is independent of the existing contrast in the image. The threshold remains approximately constant for middle and dark luminance values, but strongly increases for very dark luminance.

The range of local contrasts in our test image, measured at frequency of highest contrast sensitivity, spans up to 0.3 in Michelson measure. For such contrasts, Peli at al.[2] observed a similar behavior in a corresponding experiment for a simple stimuli. We also observe a slight increase in threshold for bright areas which is unusual.

4.2 Perceptual Contrast Scaling

The *contrast scaling* experiment derived the relation between the relative contrast measure c and JND of contrast. Such a relation is usually described by the contrast transducer function,[11] which is a power function. The contrast transducer converts contrast $G = log(L_{max}/L_{min})$, to the JND of contrast. Parameterizing the contrast G with contrast scaling from Equation (1) we can derive the relation $G(c) = c \cdot G(1)$, where $G(1)$ is the contrast in the unmodified image. Since $G(1)$ is constant for a given image, we conclude that the contrast transducer for c should also follow the power law.

The fit of the data from the experiment to a power function results in a fair consistency of perceptual response to contrast across measured luminance levels. The exponent value $\beta = 0.47$ and scale value $\alpha = 9.32$ are approximately the same for all luminance levels and the curve is only shifted along the JND axis depending on the luminance (see Equation (3)). The exponent of the contrast transducer derived by Mantiuk et al.[11] is approximately equal to 0.52 and is similar to our results obtained for the complex image.

4.3 Contrast in Complex Images

We wrap the aspect of contrast in complex images in the *contrast factor* from Equation (1) which permits obtaining a relation between two contrasts without actually measuring them. Our handling of contrast generalizes the fact that overall image contrasts is composed from several sub-band components which have varied influence on the perceived contrast. Although we made effort that our image is representative for natural scenes, we probably make a generalization which is yet to be estimated. Currently, however, the comparison to related measurements for simple stimuli does not indicate any incorrectness.

5. APPLICATIONS

We aim at maintaining perceptual uniformity in contrast scaling for complex images across wide luminance range. We employ our experimental data to parameterize *contrast factor* in Equation (1) so that we adjust contrast scaling by specifying the amount of perceived contrast change C_p in relative JND units of contrast:

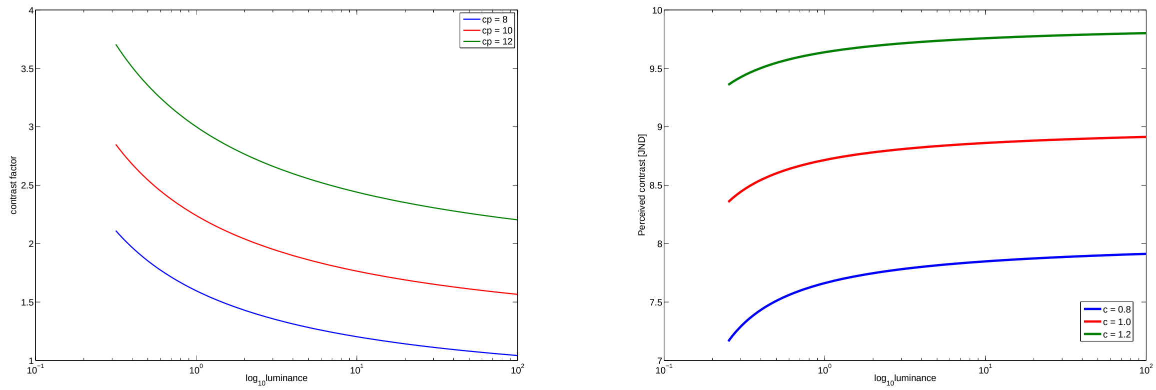
$$L(C_p) = \bar{L} \cdot \left(\frac{L}{\bar{L}}\right)^{c(C_p,L)}. \qquad (4)$$

The parameterized *contrast factor* $c(C_p, L)$ can be obtained as an inverse function of Equation (2):

$$c(C_p, L) = \left(\frac{C_p - \gamma(L)}{\alpha}\right)^{\frac{1}{\beta}} \qquad (5)$$

where C_p is a desired perceived contrast and $\gamma(L)$ is same as Equation (3).

The analysis of the parameterization $c(C_p, L)$ in Figure 6(a) reveals that the value *contrast factor* varies significantly for a given perceptual change of contrast. By taking the reverse, a fixed *contrast factor* leads to perceptual non-uniformity in contrast change of about 4 JND units across luminance range available on current displays (Figure 6(b)). Figure 6(a) also demonstrates an interesting observation that a desired decrease in contrast equal to -2 JND with respect to middle luminance, results in no contrast change in very dark areas. In the next sections we use Equation (4) to maintain perceptual uniformity in global and local contrast scaling.



(a) Inversely computing *contrast factors* to obtain the same perceived contrast.

(b) Applying the same *contrast factors* globally. It causes different perceived contrast.

Figure 6: *Influence of luminance level on perceived contrast change and on adjustment of contrast factor to maintain perceptually uniform contrast change. The values of α and β in Equations* (2) *and* (5) *are set as 9.2 and 0.47 respectively.*

5.1 Global Contrast Scaling

The global contrast scaling is obtained when the reference luminance $\bar{L}$ in Equation (4) is constant for all pixels in the image. To maintain perceptual uniformity, the exponent of a power function is dependent on the pixel's luminance value and results in an adjusted luminance mapping function. The plot in Figure 7 illustrates that high luminance requires smaller contrast change than lower luminance. Such a difference in mapping is mandated by our experiment and derived based on its model (see Figure 5), and it stays in accordance with experiments by Peli et al.[2]

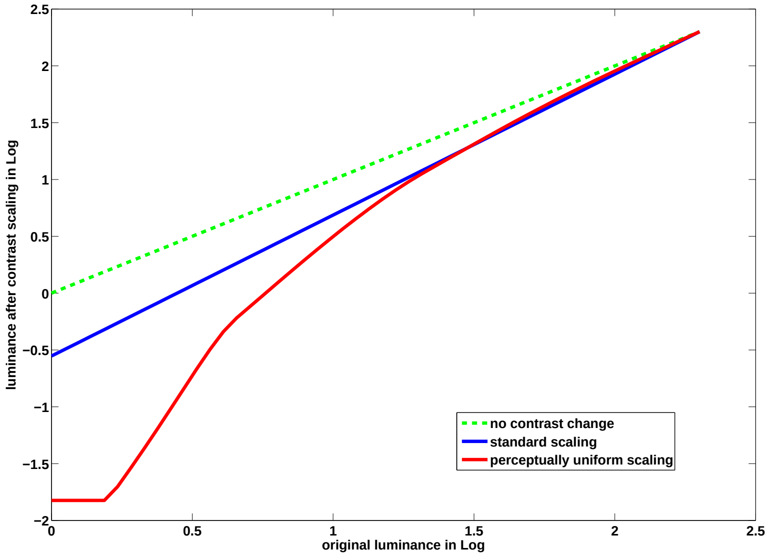


Figure 7: *Luminance mapping in perceptually uniform global contrast scaling. Mapping clipped to minimum display luminance. Refer to Section 5.1.*

5.2 Local Contrast Scaling

Adjusting the reference luminance $\bar{L}$ in equation (4) to an average of certain small area around each pixel in the image, the contrast scaling equation becomes an unsharp masking filter for enhancement of local contrasts. Analogically to previous Section 5.1, illustrate that high luminance areas require smaller contrast enhancement than lower luminance areas. Fixed *contrast factor* leads to much weaker perceived enhancement of local contrast in dark areas (see Figure 8).

6. CONCLUSIONS AND FUTURE WORK

Through psychophysical experiments, we derived a model for a perceptually uniform contrast change in complex images and demonstrated its application to global and local contrast scaling. We expect that such a new method is particularly important for displays with wide luminance range, which reduces the non-uniformity in contrast scaling of several JND units. We observed certain resemblance of our results for complex images with experiments of others performed for simple stimuli. In the next step, we plan to extend our experiments to a more representative group of test images and to extensively compare our results with current findings in psychophysics.

REFERENCES

1. H. Seetzen, W. Heidrich, W. Stuerzlinger, G. Ward, L. Whitehead, M. Trentacoste, A. Ghosh, and A. Vorozcovs, “High dynamic range display systems,” in *Proc. of ACM SIGGRAPH 2004*, 2004.
2. E. Peli, J. Yang, R. Goldstein, and A. Reeves, “Effect of luminance on suprathreshold contrast perception,” *Journal of the Optical Society of America A* **8**, pp. 1352 – 1359, August 1991.
3. W. K. Pratt, *Digital image processing*, John Wiley & Sons, Inc., New York, NY, USA, 2nd ed., 1991. ISBN 0-471-85766-1.
4. L. L. Thurstone, “A law of comparative judgment,” *Psychological Review* **34**, pp. 273–286, 1927.
5. M. M. Taylor and C. D. Creelman, “PEST: Efficient estimates on probability functions,” *J. of the Acoustical Society of America* **41**(4), pp. 782 – 787, 1967.
6. W. S. Torgerson, *Theory and methods of scaling*, John Wiley & Sons, Inc., New York, 1958.
7. G. E. Legge, “A power law for contrast discrimination,” *Vision Research* **21**, pp. pp. 457 – 467, 1980.
8. P. Whittle, “Increments and decrements: luminance discrimination,” *Vision Research* **26**(10), pp. 1677 – 1691, 1986.

Figure 8: *Standard local contrast enhancement (Top) and perceptually uniform local contrast enhancement (Bottom) by* $C_p = +4$ *JND with respect to the original image shown in Figure 1. Differences are most visible in marked areas, but are very subtle unless observed on an HDR display. Refer to Section 5.2.*

9. F. A. A. Kingdom and P. Whittle, “Contrast discrimination at high contrasts reveals the influence of local light adaptation on contrast processing,” *Vision Research* **36**(6), pp. 817 – 829, 1995.
10. G. E. Legge and J. M. Foley, “Contrst masking in human vision,” *Journal of Optical Society of America* **70**, pp. 158 – 1470, December 1980.
11. R. Mantiuk, K. Myszkowski, and H.-P. Seidel, “A perceptual framework for contrast processing of high dynamic range images,” *ACM Transactions on Applied Perception* **3**(3), pp. 286 – 308, 2006.
12. S. Daly, “The visible differences predictor: An algorithm for the assessment of image fidelity,” in *Digital Images and Human Vision*, A. B. Watson, ed., pp. 179–206, MIT Press, 1993. ISBN: 0-262-23171-9.