Perceived Image Contrast and Observer Preference II. Empirical Modeling of Perceived Image Contrast and Observer Preference Data

Anthony J. Calabria▲
Sun Chemical, Carlstadt, New Jersey, USA

Mark D. Fairchild ▲
Munsell Color Science Laboratory—Rochester Institute of Technology, Rochester, New York, USA

Psychophysical experimentation was performed on the perceived contrast of color images and its effect on observer preference. Goals of this research included the following: investigation into the roles of image lightness, chroma and sharpness manipulations on perceived image contrast; modeling the perception of image contrast with physical image parameters; the relation of perceived contrast of an image to the most preferred version of that image; and the generation of a large scale image contrast data set for later use in image difference/quality metric development. These goals were undertaken by administration of soft copy paired-comparison experiments of perceived image contrast and observer preference. These tests were performed over four months, by more than seventy observers. Perceived image contrast was determined to be scalable with respect to lightness, chroma, and sharpness manipulations. Perceived image contrast scales were image independent between five pictorial images. Significant contrast differences between images of identical white and black points were perceived, demonstrating that image white and black points do not solely determine image contrast. Significant image contrast differences were found between full color images and their achromatic versions, thus demonstrating that perceived image contrast is a function of image chroma information. It was also shown that the perceived contrast of achromatic images is higher than perceived contrast of very low chroma images. Perceived image contrast was empirically modeled using physical parameters of the images. Values based on image lightness, chroma, and sharpness information were used to model the perception of image contrast in a relative and stand-alone sense. In *Reproduction Versus Preferred* (RVP) contrast modeling, image parameters were taken relative to the most preferred version of the image. In *Single Image Perceived* (SIP) contrast modeling, parameters of single images were fit to scales of perceived contrast. RVP contrast modeling illustrated that image contrast is perceived relative to the most preferred version of that image. SIP contrast analysis indicated differences in perceived contrast were perceived image independent, and reinforced perception of image contrast relative to the most preferred version of an image. This concept of contrast perception relative to the preferred image indicates image contrast can be described without knowledge of an original scene in the image capture sense or knowledge of an original image in the image reproduction sense.

Journal of Imaging Science and Technology 47: 494–508 (2003)

Introduction

It has been shown that certain perceptual attributes of images have a nonmonotonic relationship to image quality.[1,2] Image quality as a function of colorfulness has been shown to increase to maximum, then decrease, resulting in an "inverted U" shape (referred to as the *preference–percept relationship*). Engledrum has proposed a means of empirically modeling nonmonotonic image percepts versus image quality.[2] Empirical modeling is used as a means of describing data based on image characteristics to help develop image quality/difference models.

Image contrast is commonly defined in terms of an image tone reproduction curve (TRC). In image capture, the TRC represents the transformation from the actual scene luminance to the luminance of the captured image. In image reproduction, the TRC often represents the luminance transform from an original image to its reproduction. Contrast is commonly thought of as the slope of the straight-line portion of the TRC between an image and its reproduction. The term gamma (γ) is often used to describe the slope of this portion of a TRC on log–log coordinates.[3] This straight-line portion of a TRC represents the midtone region of the image, where there is a consistent separation of tone.

A preliminary difficulty in using a TRC's gamma to define contrast is the need for a very well behaved TRC. Actual image luminance reproduction curves are not necessarily of the ideal sigmoidal nature where derivatives can be used to find the point of inflection where gamma should be calculated. Another shortcoming in defining image contrast in terms of a TRC requires an

Original manuscript received January 7, 2003

▲ IS&T Member

original and a reproduction. Contrast defined by a TRC also makes it possible for two sets of images to have similar "gammas" despite having very different white and black points, in which case the gammas may not coincide with the visual percept of image contrast[3–5] (hereafter referred to as *perceived image contrast*). The TRC also does not contain any color information; therefore a TRC-based contrast definition assumes images have the same contrast as long as their achromatic information is the same. It seems possible that the Helmholtz–Kohlrausch effect (brightness increases as a function of chroma) may have an effect on perceived image contrast.

Terminology

In this research, previously acquired experimental data of image preference and perceived image contrast[6] are empirically modeled using physical image characteristics. In Reproduction Versus Preferred (RVP) contrast modeling, perceived image contrast and image preference data are fit using image characteristics relative to the same characteristics of the most preferred image. The variable κ_L represents the relative image characteristic chosen to describe "lightness contrast" relative to the most preferred image, i.e., κ_C and κ_S are similarly defined for "chroma contrast" and "sharpness contrast", (see Eqs. 2 and 4). The image characteristics chosen are described in their associated sections. The term RVPκ_L represents the modeled value of RVP contrast as a function of the relative lightness characteristic (RVPκ_C and RVPκ_S are similarly defined for RVP contrast from chroma and sharpness, (see Eqs. 1, 3, and 5)). RVPκ represents the modeled perceived image contrast value as a function of relative lightness, chroma, and sharpness characteristics (see Eq. (6)).

In Single Image Perceived (SIP) contrast modeling, the perceived image contrast and image preference data were modeled as a function of single image characteristics. Here, κ_L represents the image characteristic chosen to describe "lightness contrast" in a single image, (κ_C and κ_S are similarly defined for "chroma contrast" and "sharpness contrast", (see Eqs. 7, 9, and 11)). SIPκ_L represents the modeled value of SIP contrast as a function of the lightness characteristic (SIPκ_C and SIPκ_S are similarly defined for SIP contrast from chroma and sharpness, (see Eqs. 8, 10, and 12)). SIPκ represents the modeled perceived image contrast value of a single image as a function of relative lightness, chroma, and sharpness characteristics (see Eq. 13).

Procedure

Independent interval scales of perceived image contrast and image preference have been collected by means of a series of soft copy, paired-comparison experiments.[6] These experiments independently investigated the influence of lightness transfer functions, relative chroma amount, and sharpness on perceived contrast. It was learned that the perceived contrast is related to the three aforementioned image attributes. It was also learned that results of these experiments indicate perceived image contrast has a nonmonotonic relationship with image preference; where image preference increases as a function of perceived contrast, reaches a maximum, then decreases.

Having demonstrated the ability to scale images for both perceived image contrast and image preference, it was of interest whether these relationships can be modeled based on image characteristics. Physical image characteristics were used to empirically model scales of perceived image contrast. Image preference was then modeled as a function of perceived image contrast.

For the purpose of this research, perceived image contrast has been defined below in terms of an image and an observer's most preferred version or internal ideal representation of that image.

Perceived image contrast: the perception of the rate of change of the relative luminance of image elements of a reproduction as a function of the relative luminance of the same image elements of the preferred/ideal version of the image.

For these reasons, image parameters have been used relative to the most preferred image for Reproduction Versus Preferred contrast modeling. RVP contrast analysis can be thought of as using the most preferred image (*25sc*) from Ref. 6 as the "original," and the other image manipulations as "reproductions" of the most preferred. Therefore, RVP contrast is the perception image contrast relative to what has been determined to be the most preferred version of that image.

Although RVP contrast approaches to the goal of modeling perceived image contrast as defined for this research, it requires both an image pair and image preference information, neither of which are always available. For these reasons, modeling perceived image contrast data was also attempted using single image statistics. In Single Image Perceived contrast modeling, physical image parameters from one image are used as model parameters in an attempt to predict perceived contrast. SIP contrast was also used to examine contrast differences between images and their most preferred version.

For purposes of modeling, five was added to the mean perceived contrast scale values to ensure an all-positive scale. Because the achromatic image was judged differently than the chromatic images, modeling was performed on the chromatic images. In upcoming plots of perceived contrast and preference modeling, image numbers are organized as shown in Table I. Image numbers *1–6* represent chroma-manipulated images, numbers *7–26* represent lightness-manipulated images, and number *27–34* represent sharpness-manipulated images.

Perceived Image Contrast Modeling

Reproduction Versus Preferred (RVP) Contrast Modeling. It was decided that the RVP contrast model should consist of single parameters for each of the lightness-contrast, chroma-contrast, and sharpness-contrast relationships studied here. Since sharpness-contrast manipulations were functions of image lightness channel, the achromatic contrast parameters may be similar.

RVP Lightness-Contrast Modeling. Past research of image contrast has shown the importance of the tone reproduction curve (TRC). The slope of the straight-line portion of the TRC is commonly used as a metric of image contrast. An analogous function in the RVP analysis could be mapping of relative pixel achromatic parameters. Parameters chosen for this model fitting were pixel lightness (L*), luminance (Y), and brightness (L**). L** has been defined as a predictor of the Helmholtz–Kohlrausch effect.[7] Pixel lightness, luminance and brightness were plotted relative to the corresponding pixels of the most preferred image (25sc).

TABLE I. Image number and name for upcoming plots. Image numbers *1–6* represent chroma-manipulated images. Image numbers *7–26* represent lightness-manipulated images. Image numbers *27–34* represent sharpness-manipulated images.

Image number	name
1	1.20c
2	1.00c
3	0.80c
4	0.60c
5	0.40c
6	0.20c
7	inc_sig_10
8	pow_–1.05
9	lin_–0.200
10	hist_equal
11	lin_–0.150
12	inc_sig_15
13	lin_–0.100
14	inc_sig_20
15	inc_sig_25
16	lin_–0.0500
17	pow_1.00
18	dec_sig_25
19	lin_0.0500
20	dec_sig_20
21	lin_0.100
22	dec_sig_15
23	lin_0.150
24	lin_0.200
25	pow_0.950
26	pow_0.900
27	250sc
28	200sc
29	150sc
30	100sc
31	75sc
32	50sc
33	25sc
34	0sc

When plotting these parameters relative to the most preferred image, it was often difficult to determine the "straight-line" portion of the curve. Figures 1(a) through 1(d) illustrates that not only is there difficulty in defining a single point of inflection that would represent the "straight-line" portion, but there is also a substantial range of output values for each input value. The range of output lightnesses shown in Fig. 1 is mostly the result of the sharpening manipulations. *Unsharp masking* causes increases and decreases in lightness to better define edges. The greater the sharpening amount, the greater the magnitude of edge lightness scaling. The most preferred image was an image that had been sharpened. The following procedure was used to consistently determine where slope measurements were calculated. The RVP curve of image L* was plotted as a function of the most preferred image L*. The mean output image L* was calculated using the *25sc* image L* as input (central line in Fig. 1). Slopes of this function were calculated at 40%, 45%, 50%, 55%, and 60% of the maximum output image L*. The three greatest, consecutive slopes were averaged. This procedure was repeated for all parameters requiring such data.

Equation (1) was derived as a model of perceived image contrast relative to the preferred image (see Table II for full model parameters and error metrics). The averaged slope of the L* RVP curve is represented by the variable κ_L.

$$RVP\kappa_L = 2.640\kappa_L + 1.863 \tag{1}$$

$RVP\kappa_L$ represents RVP contrast from lightness. The fit of $RVP\kappa_L$ to the image data is shown in Fig. 2. Figure 2 illustrates $RVP\kappa_L$ does contain some sharpness-contrast information, and no chroma-contrast information.

RVP Chroma-Contrast Modeling. The mean pixel-wise image chroma ratio between an image and the preferred-image chroma fit the perceived chroma-contrast data quite well (Eq. (2)). Chroma-contrast is represented by the variable $RVP\kappa_C$ defined in Eq. (3). $RVP\kappa_C$ represents RVP contrast from chroma. In Fig. 3 it is observed the chroma-contrast is fit with very little effect on images manipulated for lightness-contrast or sharpness-contrast.

$$\kappa_c = \overline{\left(\frac{\text{image } C^*_{ab}}{\text{preferred image } C^*_{ab}}\right)} \tag{2}$$

$$RVP\kappa_C = 2.00\kappa_C + 2.097 \tag{3}$$

RVP Sharpness-Contrast Modeling. Since the actual sharpening filter parameters are not known, several parameters were chosen for modeling sharpness-contrast. Since it is known the sharpening was performed on the image lightness channel, high frequency images were created for various image attributes (lightness, luminance, brightness for example). A pixel-wise ratio image between the high frequency images and the high frequency image of the most preferred image (*25sc*) was created. The ratio image was then averaged, resulting in a single number related to sharpness (see Eq. (4) below). One means of generating the high frequency image was *SOBEL* filtering in IDL. A second filter was generated based on the analysis of the frequency power spectra of sharpness-manipulated images.

$$\kappa_S = \overline{\left(\frac{HF_i}{HF_p}\right)} \tag{4}$$

This filter was generated using a Gaussian function that peaked at the highest frequencies (see Fig. 4). Equation (4) was used to define the parameters of sharpness contrast. HF_i represents the high frequency images, HF_p represents the high frequency image of the most preferred image.

This filter was designed to reduce the influence of the lowest frequencies and include the frequencies amplified by the unsharp masking. Equation (5) was derived to model RVP contrast from sharpness ($RVP\kappa_S$).

$$RVP\kappa_S = 1.038\kappa_S + 3.988 \tag{5}$$

The variable κ_S represents the mean ratio of high-pass lightness images from Eq. (4). In Fig. 5 is shown the sharpness data predicted by $RVP\kappa_S$. The sharpness-contrast model does not affect the chroma-contrast data. The slight influence of the sharpness-contrast model on the lightness-contrast data was expected. Since the sharpness manipulations were based on the lightness channel, and the sharpness-contrast model is also lightness-based, there was some influence expected.

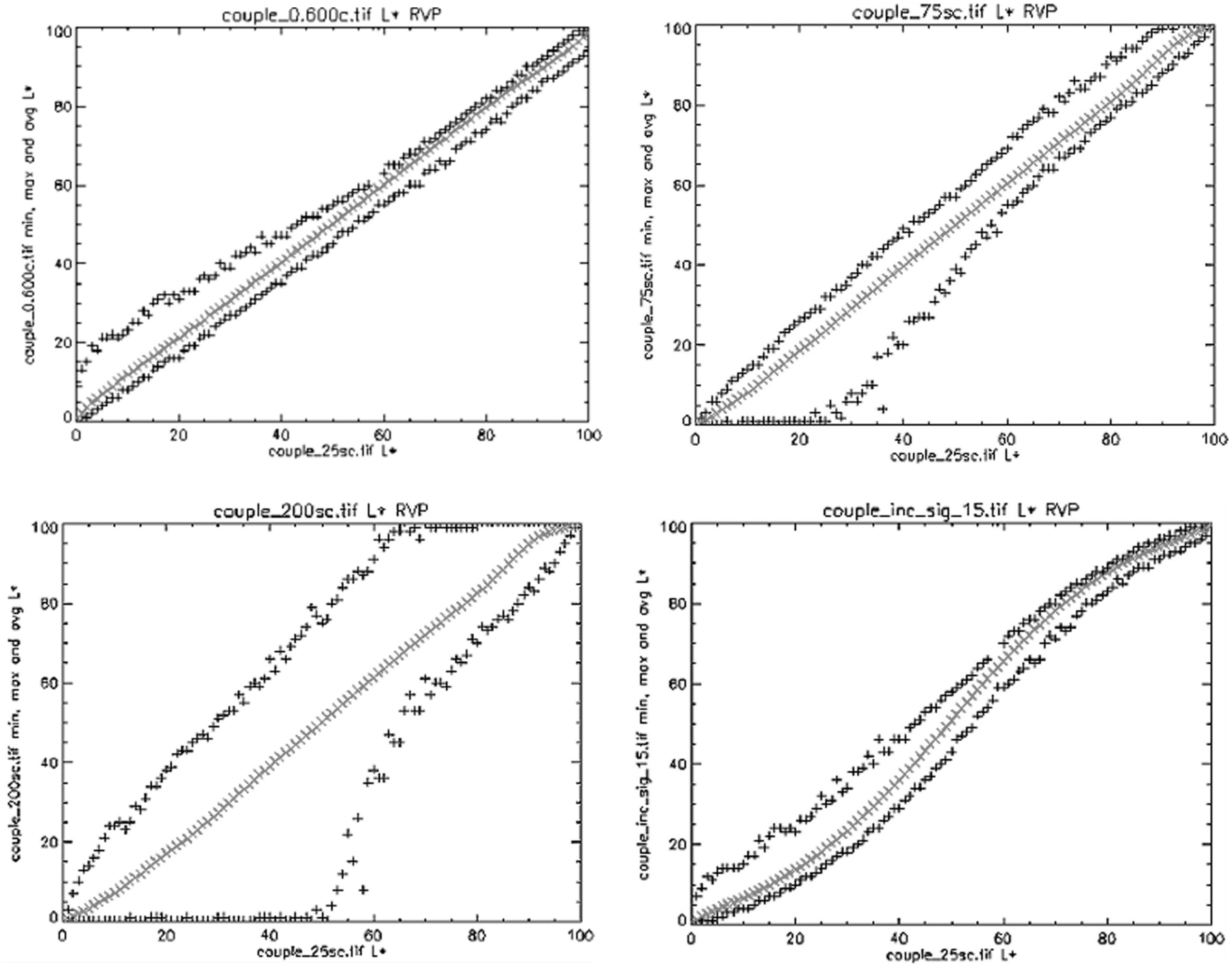

Figure 1. Image L* channel shown as a function of the most preferred image (*25sc*) L* channel.

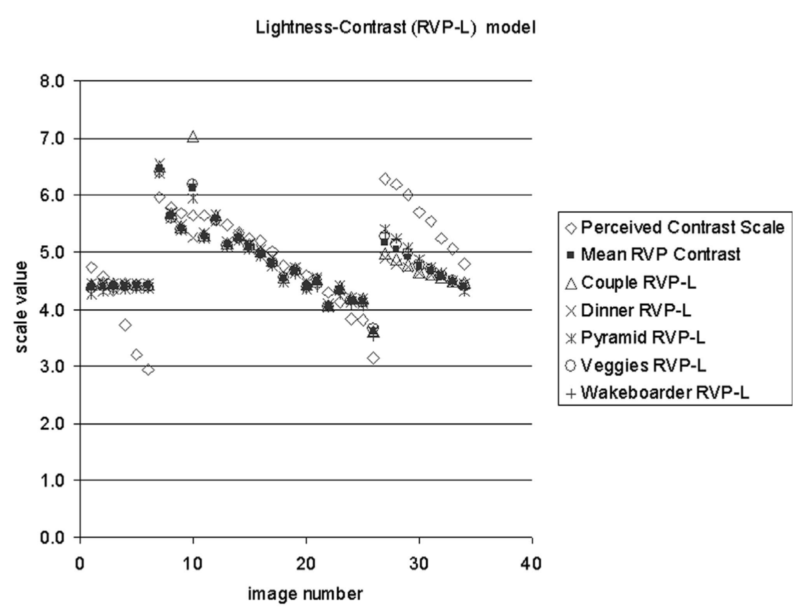

Figure 2. Perceived image contrast scale with modeled image RVPκ_L. Images are numbered in order of decreasing contrast for chroma-contrast (Image numbers *1–6*), lightness-contrast (Image numbers *7–26*), and sharpness-contrast (Image numbers *27–34*)

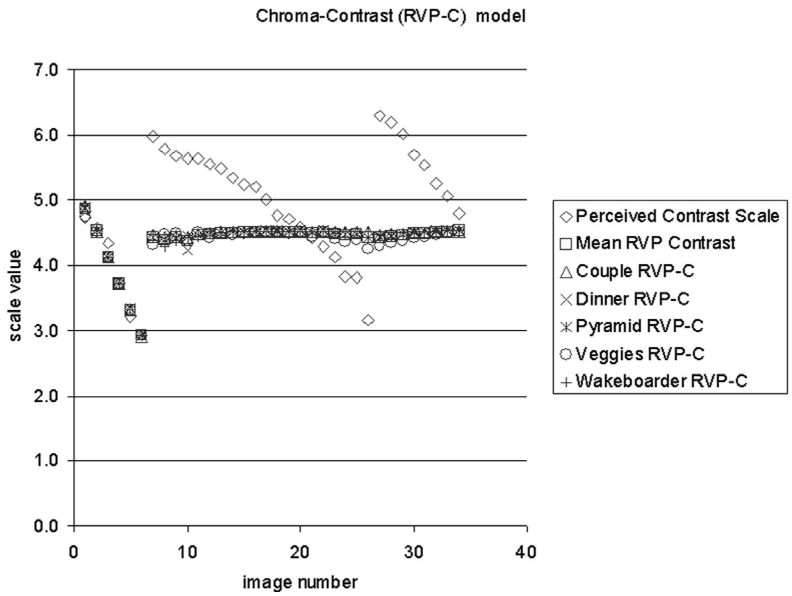

Figure 3. Perceived image contrast scale with modeled image $RVP\kappa_C$. Images are numbered in order of decreasing contrast for chroma-contrast (Image numbers *1–6*), lightness-contrast (Image numbers *7–26*), and sharpness-contrast (Image numbers *27–34*).

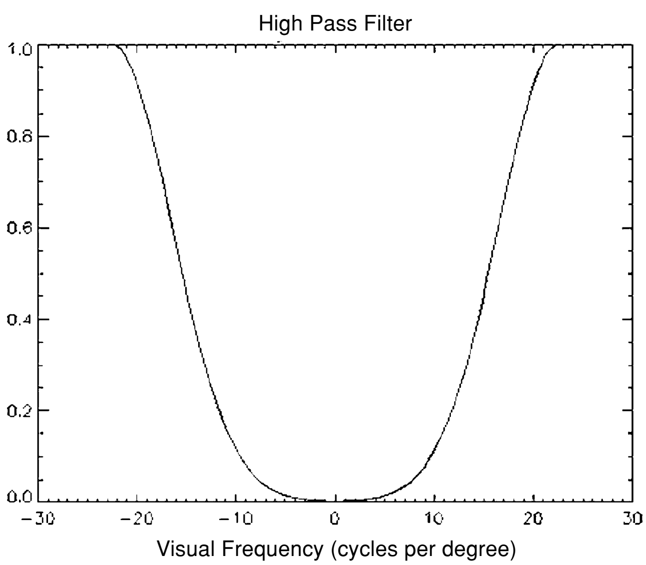

Figure 4. High-Pass Filter used for $RVP\kappa_S$ calculations.

RVP Contrast Modeling. The parameters defined by variables κ_L (slope of L* RVP curve), κ_C (mean RVP chroma ratio), κ_S (mean high-pass image ratio) plus an offset parameter were used to model the full mean contrast scale. For the sake of simplicity, linear regression was used.

$$RVP\kappa = -0.307 + 2.097\kappa_C + 1.109\kappa_L + 0.547\kappa_S \quad (6)$$

Equation (6) was fit to the mean contrast scale minimizing RMS error. The value $RVP\kappa$ represents *RVP* contrast; the perceived contrast of an image relative to the most preferred version of that image.

Parameters from the RVPκ, $RVP\kappa_L$, $RVP\kappa_C$, and $RVP\kappa_S$ contrast models are shown in Table II for comparison. In each case, the RVPκ parameter weight is unequal to the same parameter's weight in the individual models, which is not surprising. However, the weights associated with the κ_C and κ_S parameters are less than 5% different from their weights in the individual models, while the κ_L weight is 27% less than in the $RVP\kappa_L$ model. One possible explanation is the κ_S term could be influencing the prediction of the lightness-contrast data.

Figures 6 and 7 illustrate the goodness-of-fit of the $RVP\kappa$ model. It is observed the region of highest model error is in the high-contrast lightness-manipulated images. The manipulation associated with the greatest

Table II. Image RVPκ Models with Model Parameters and Weights.

	Control Model			
Parameter	RVPκ	RVPκL	RVPκC	RVPκS
κC	2.097	0.000	2.000	0.000
κL	1.928	2.640	0.000	0.000
κS	1.054	0.000	0.000	1.038
offset	–0.307	1.863	2.517	3.988

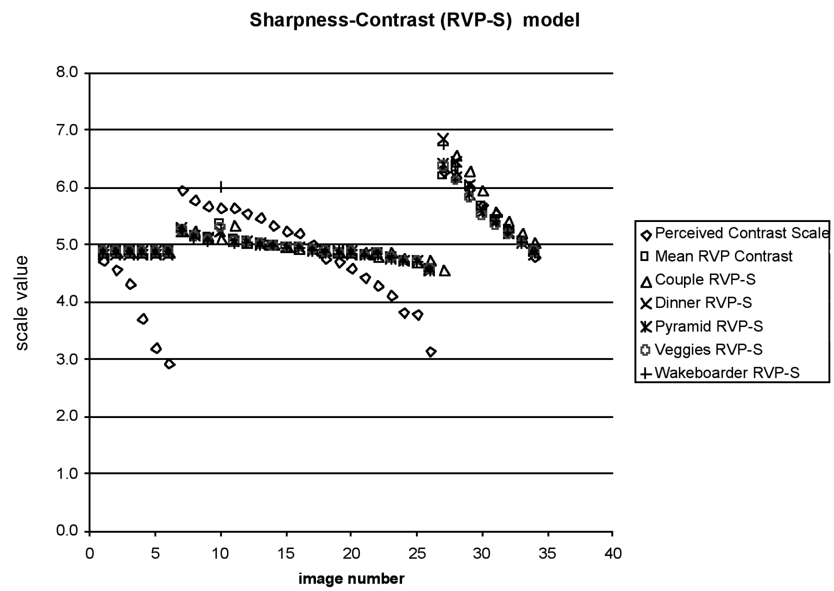

Figure 5. Perceived image contrast scale with modeled image $RVP\kappa_S$. Images are numbered in order of decreasing contrast for chroma-contrast (Image numbers *1–6*), lightness-contrast (Image numbers *7–26*), and sharpness-contrast (Image numbers *27–34*).

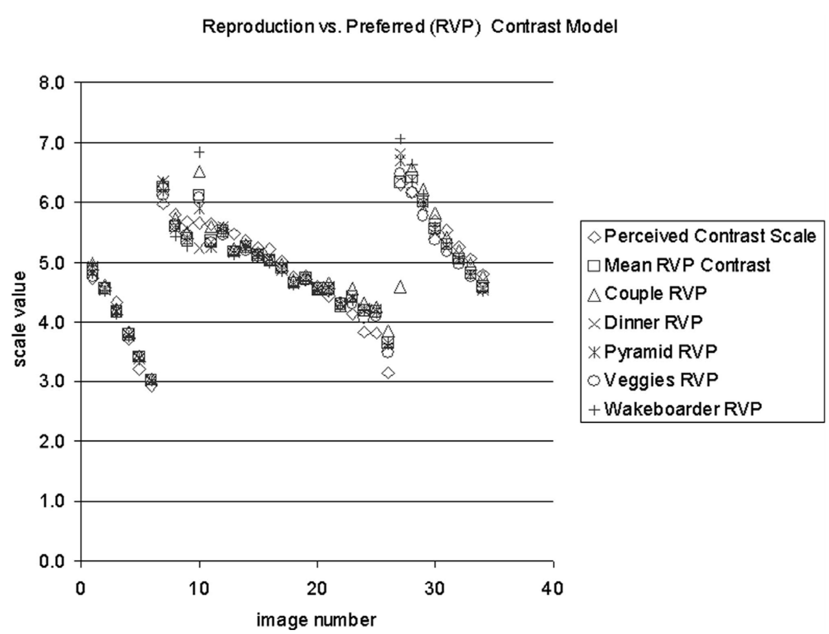

Figure 6. Perceived image contrast scale with modeled image RVPκ.

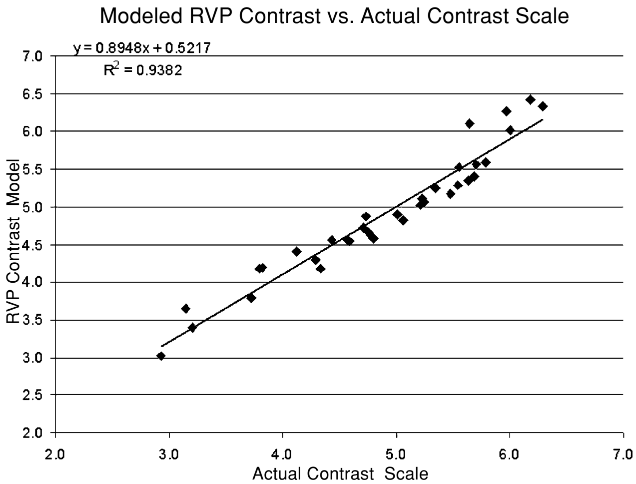

Figure 7. Mean Modeled RVP contrast scale versus actual contrast scale.

model error is the histogram equalization. This is most likely due to the calculation of the slope of the RVP L* curve. Since the histogram equalization of image L* is dependent on the input image L*, the transformation can vary based on image content. This error indicates the *RVP*κ model presented in Eq. (6) may not be adequate for all possible image manipulations, although seems appropriate for the manipulations more closely resembling image reproduction transformations.

RVP Contrast Summary. The most common definition of image contrast is the slope of the straight-line portion of the tone-reproduction curve between an original and a reproduction (gamma). This concept of defining contrast with parameters relative to an image pair was used to generate an empirical model of image contrast between an image and the most preferred reproduction of that image. Equation (6) defines perceived image contrast relative to the most preferred version of that image using metrics of relative lightness, chroma, and sharpness information (*RVP*κ). The image associated with the greatest error was the histogram-equalized image. Since this transform is performed as a function of image content, the κ_L parameter is inadequate at describing perceived lightness contrast. This being said, the *RVP*κ model of perceived contrast seems to be a reasonable descriptor for perceived image contrast when simple achromatic transforms are used, and may be a reasonable starting point for a more robust model of perceived image contrast.

Single Image Perceived (SIP) Contrast. In the previous section, perceived image contrast was modeled as a function of an image and the most preferred version of that image. In this section, image contrast is treated as a single image parameter. The concept of *Single Image Perceived (SIP)* contrast is based on observers' ability to look at a single image and describe the image as "high-contrast" or "low-contrast." The influence of single image characteristics on the perception of image contrast was investigated. Image statistics were chosen which were expected to influence lightness-contrast, chroma-contrast, and sharpness-contrast. Linear regression was used as in the previous model.

Since there is no reason to expect similar manipulations of different test images to have similar colorimetric statistics, SIP contrast models were generated for the five pictorial test images and averaged. The average SIP contrast model was fit to the all-positive linked perceived contrast scale.

SIP Lightness-Contrast Modeling. Image statistics considered for SIP lightness-contrast (SIPκ_L) included standard deviation of image lightness (L*), luminance (CIEXYZ Y), and Michelson contrast of *Y*. Since all images had black point of $Y = 0$, Michelson contrast yielded values of 1 for all images. Standard deviations of lightness and luminance were not significantly different from each other. Since this research primarily deals with perceived contrast, the perceptual-based $SIP\kappa_L$ model was preferred (Eq. (8)).

$$\kappa_L = \sigma^2\,(\mathrm{L}^*) \tag{7}$$

$$SIP\kappa_L = +\,0.014\kappa_L + 3.86 \tag{8}$$

The variable κ_L is defined as the standard deviation of image lightness. Figures 8 and 9 illustrate the significance of this parameter on the sharpness-contrast data. The value of $SIP\kappa_L$ had no effect on the chroma-contrast data.

SIP Chroma-Contrast Modeling. Image statistics considered for SIP chroma-contrast (SIPκ_C) included standard deviation, mean and median image chroma (C^*_{ab}). All three parameters predicted chroma-contrast relatively well.

$$\kappa_C = \sigma^2\,(C^*_{ab}) \tag{9}$$

$$SIP\kappa_C = 0.118\kappa_C + 2.496 \tag{10}$$

Since the chroma-based statistics predicted the scale equivalently, κ_C is defined as standard deviation of chroma (Eq. (9)) in $SIP\kappa_C$ (Eq. (10)) for continuity with the lightness-contrast parameter. The parameter chosen for the chroma-contrast model seems to have little to no effect on the lightness or sharpness-contrast data (Figs. 10 and 11).

SIP Sharpness-Contrast Modeling. Image statistics considered for SIP sharpness-contrast (SIPκ_S) were similar to those in the RVP sharpness-contrast metric ($RVP\kappa_S$). Mean, median and standard deviation of *SOBEL* filtered L* and Y images were considered. Similar statistics of the high frequency L* and Y images generated with the filter described in the RVP section were also considered. Standard deviation of the high frequency L* image (Eq. (11)) fit the data best and was used as κ_S in Eq. (12).

$$\kappa_L = \sigma^2\,(\mathrm{L}^*) \tag{11}$$

$$SIP\kappa_S = 915.251\kappa_S + 4.073 \tag{12}$$

Figures 12 and 13 indicate the sharpness-contrast metric does influence the lightness-contrast data. The chroma-contrast data appear independent of $SIP\kappa_S$.

SIP Contrast Modeling. The parameters κ_L (standard deviation of image lightness), κ_C (standard deviation of image chroma), and κ_S (standard deviation of high-passed

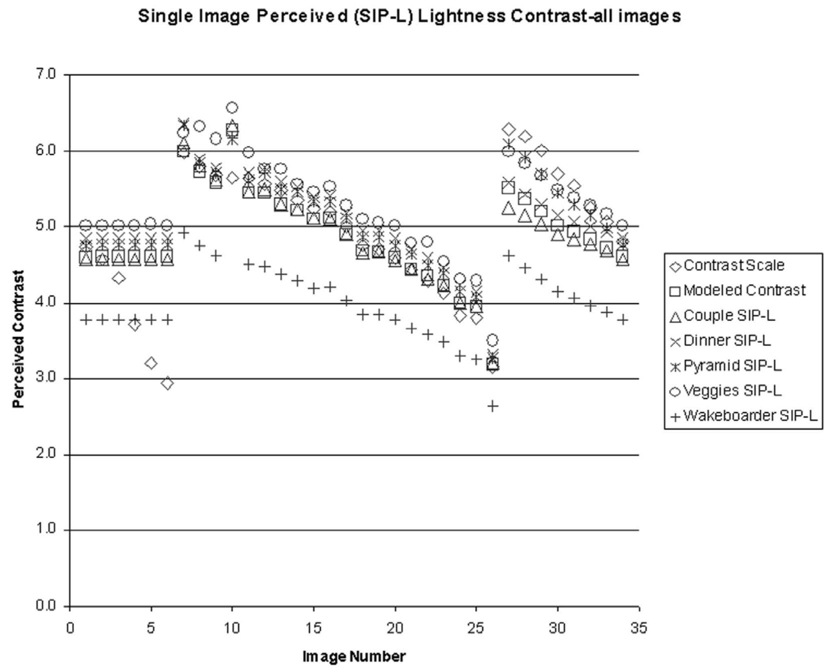

Figure 8. Perceived image contrast scale with modeled image $SIP\kappa_L$ for all pictorial images.

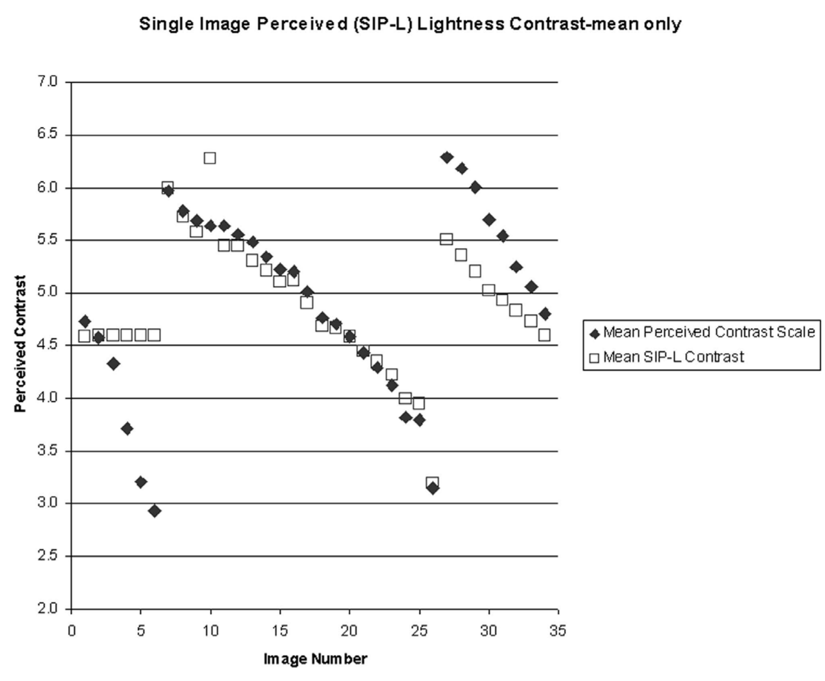

Figure 9. Mean perceived image contrast scale with modeled image $SIP\kappa_L$.

lightness) were regressed to the all-positive linked perceived contrast scale. Equation (13) was developed to model the perceived contrast of a single image ($SIP\kappa$).

$$SIP\kappa = -1.505 + 0.131\kappa_C + 0.151\kappa_L + 666.216\kappa_S \qquad (13)$$

Figures 14 and 15 illustrate the goodness of fit of SIPκ to the mean perceived contrast data. From Fig. 14 the image dependence of this model is clearly obvious. This was expected since there is no reason to expect images of different subject matter to have similar colorimetry statistics (standard deviation of chroma, for example). The only significant outlier noticeable in Fig. 15 is again the histogram equalization manipulation. It is believed the histogram-equalized images are predicted poorly for the same reasons discussed in the RVPκ section. Scales for all other manipulations are predicted well.

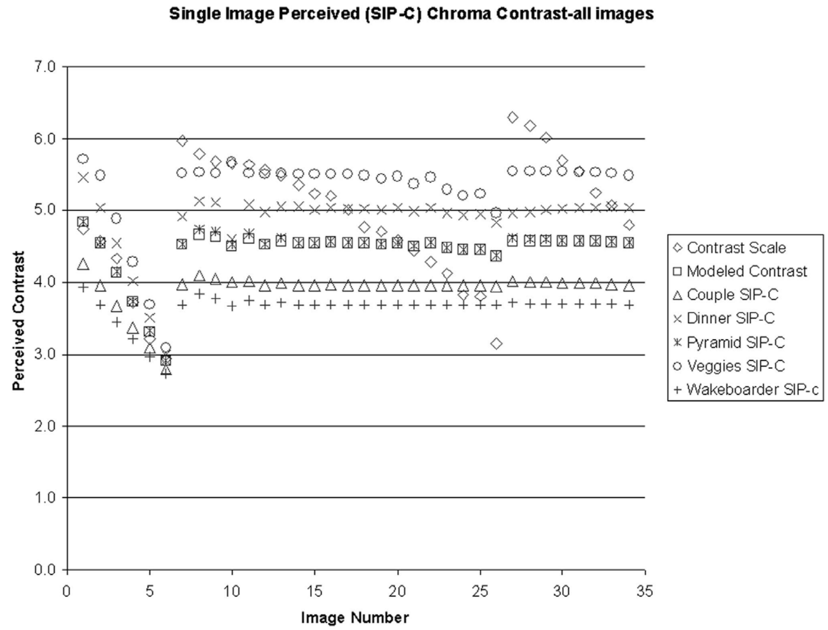

Figure 10. Perceived image contrast scale with modeled image $SIP\kappa_C$ for all pictorial images.

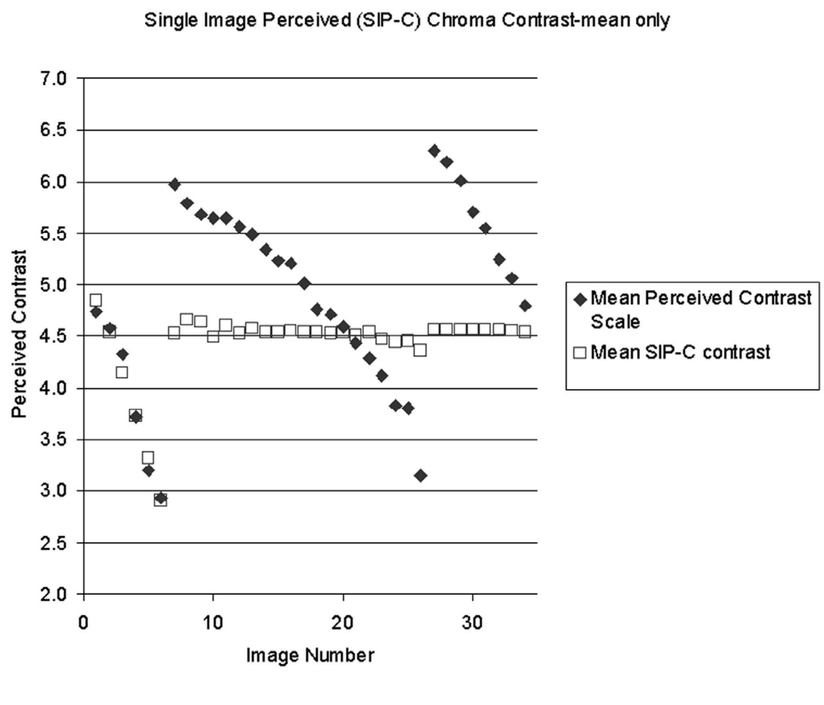

Figure 11. Mean perceived image contrast scale with modeled image $SIP\kappa_C$.

Images of similar mean perceived contrast have differences in *SIP*κ, which appear to be a scale factor from the mean. The apparent image dependent scale factor indicates there may be another factor related to the images content that may bring the image dependent SIPκ scales together. Image parameters and their associated *SIP*κ weights are shown in Table III.

The parameter weights in the *SIP*κ model resemble the weights for the $SIP\kappa_L$ and $SIP\kappa_C$ models. The weight of the κ_C term is approximately 30% lower in the SIPκ model than in the $SIP\kappa_S$ model. It is misleading to investigate the parameter weights of a model for significance to perceived contrast. The magnitude of the $SIP\kappa_S$ term is on the order of 1/10000th the magnitude of the $SIP\kappa_L$ or $SIP\kappa_C$ terms.

Despite image dependency, the strength of the *SIP*κ contrast model is the ability to quantify differences in perceived contrast. Subtracting image *SIP*κ from the

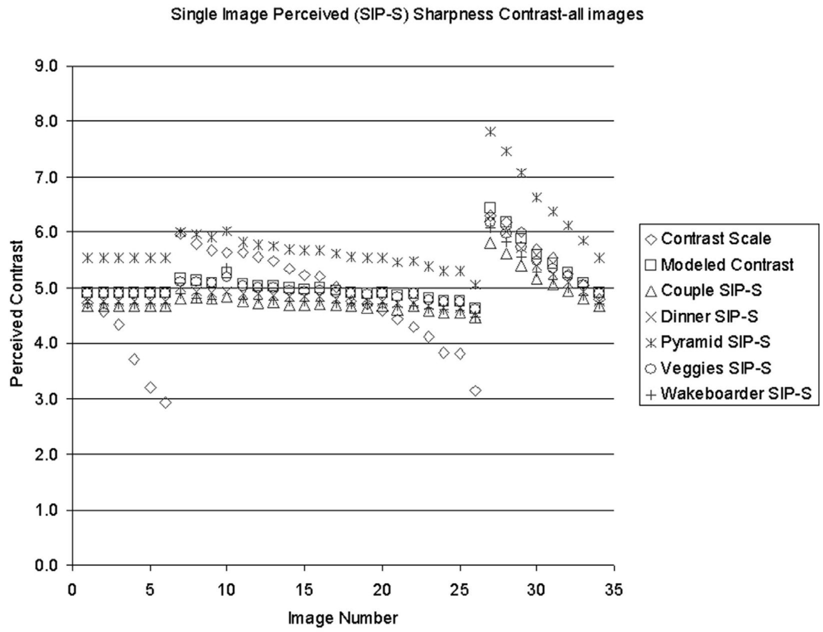

Figure 12. Perceived image contrast scale with modeled image $SIP\kappa_S$ for all pictorial images.

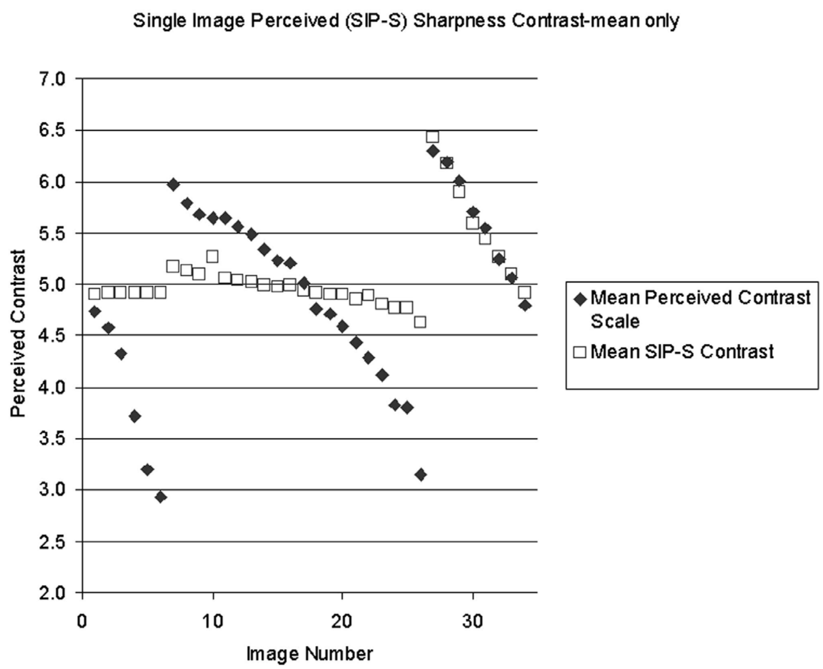

Figure 13. Mean perceived image contrast scale with modeled image $SIP\kappa_S$.

TABLE III. Image *SIPκ* with Model Parameters

	Control Model				
Parameter	SIPκ	delta SIPκ	SIPκL	SIPκC	SIPκS
κS	666.216	670.883	0.000	0.000	915.251
κC	0.131	0.151	0.000	0.118	0.000
κL	0.151	0.136	0.194	0.000	0.000
offset	–1.505	–1.505	0.386	2.496	4.073

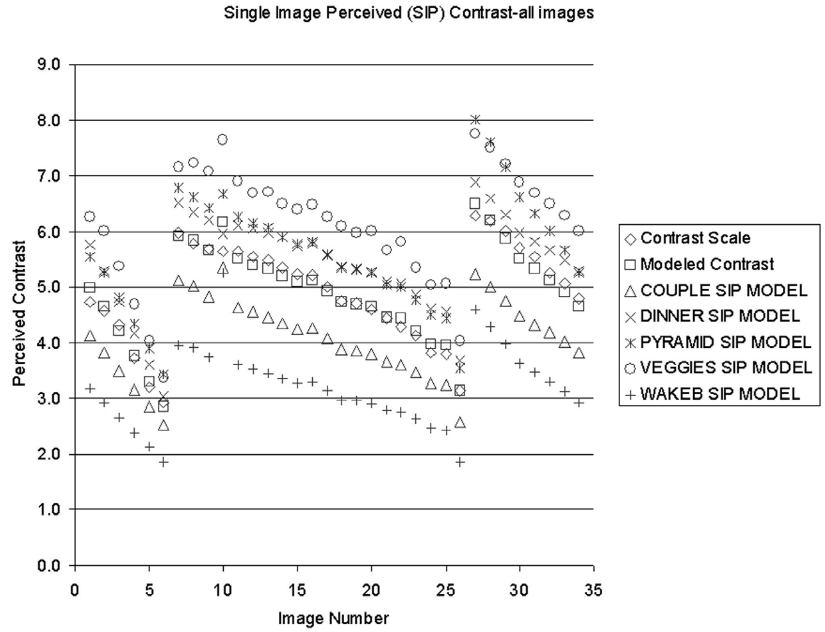

Figure 14. Perceived image contrast scale with modeled image *SIP*κ for all pictorial images.

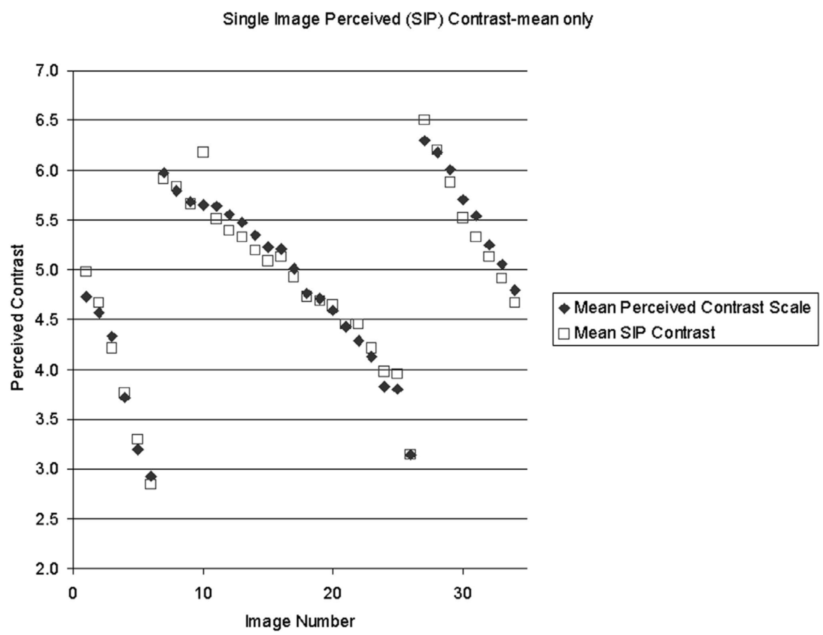

Figure 15. Mean perceived image contrast scale with modeled image *SIP*κ for all pictorial images.

most preferred image SIPκ models the difference between their corresponding perceived image contrast scale values.

$$C_i - C_p = SIP\kappa_i - SIP\kappa_p = \Delta SIP\kappa \qquad (14)$$

In Eq. (14) the actual perceived contrast scale value of an image is C_i or C_p (subscripted i for image and p for preferred), and the modeled perceived contrast of those same images are $SIP\kappa_i$ or $SIP\kappa_p$ (subscripted similarly). Figures 16 and 17 illustrate these differences are image independent.

Single Image Perceived (SIP) Contrast Summary. *SIP*κ, an image dependent model of perceived image contrast in a single image was developed based on colorimetric characteristics of a single image (Eq. (13)). Although the *SIP*κ model cannot be used to predict per-

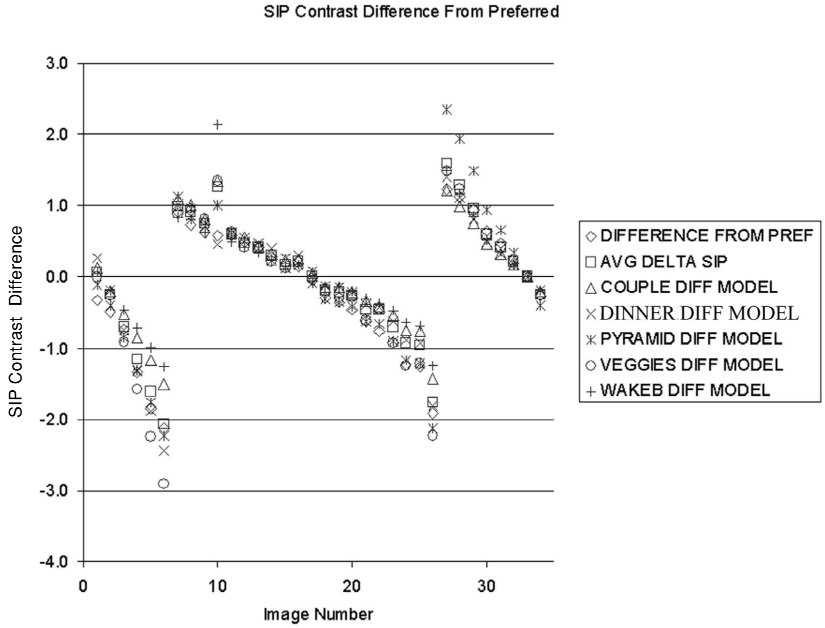

Figure 16. *SIPκ* difference versus image number.

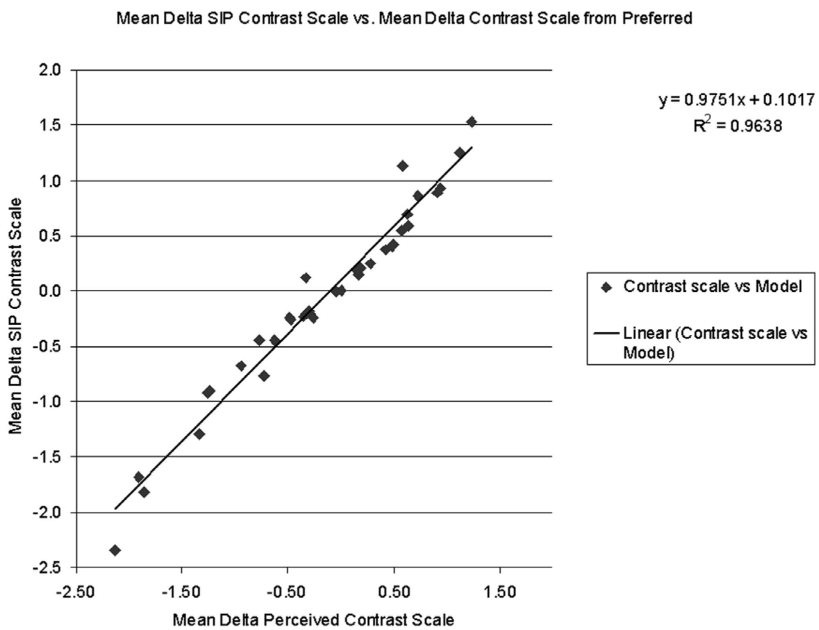

Figure 17. Mean *SIPκ* contrast difference versus actual mean perceived contrast scale difference.

ceived contrast differences between images of different subject matter, perceived contrast differences between images of the same subject matter can be predicted (Eq. (14)). In addition, perceived image contrast differences of image contrast manipulations performed on images of different subject matter can be predicted. The description of perceived contrast differences using $\Delta SIP\kappa$ is intuitive since images perceived of equal contrast have an *SIPκ* difference of zero.

Perceived Image Contrast Model Fitting Conclusions. Mathematical model fitting of perceived contrast data was attempted in two independent manners. The first method of model fitting was to take physical parameters of an image, relate them to the most preferred version of that image, and use that relationship to define the perception of image contrast. This model was called the *Reproduction Versus Preferred* contrast model (*RVPκ*). This attempt was to determine if the perception of image

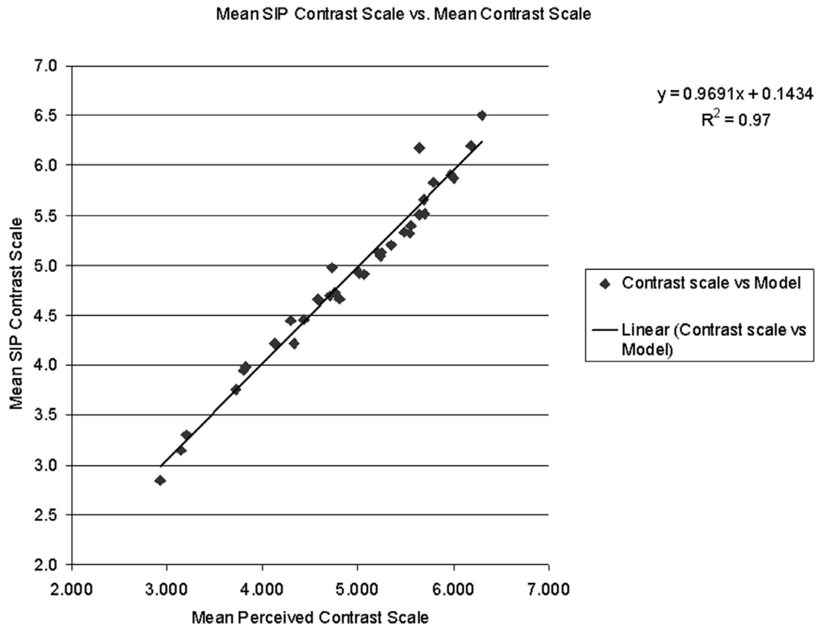

Figure 18. Mean modeled SIP image preference versus actual image preference scale.

contrast in a single image could be described by its relationship to what observers would perceive to be the most preferred version of that image. RVP contrast was modeled as a function of the slope of the straight-line portion of an RVP lightness curve, the mean ratio of image chroma to preferred image chroma, and the mean ratio of image high frequency information to that of the most preferred image. The *RVP*κ contrast model (Eq. (6)) enables the description of perceived image contrast relative to the most preferred version of that image.

The second method of perceived contrast model fitting was the generation of a single image perceived contrast metric. The prediction of *Single Image Perceived* contrast was attempted since contrast is commonly judged in images without reference to an original scene or an original image (as is the definition of image contrast). An image dependent model of SIP contrast (*SIP*κ) was fit in which similar manipulations of different test images were proportional. An image independent model of SIPκ difference (Eq. (14)) from the most preferred image was developed. Differences in SIP contrast can predict similar perceived contrast manipulations performed on images of different subject matter.

Image Preference Modeling

Two empirical models of perceived image contrast have been developed. The first model, *RVP*κ, defines perceived contrast of an image relative to the most preferred version of that image. The second model, *SIP*κ, defines the contrast of a single image relative to perceptual attributes of that image. The *SIP*κ contrast model is more intuitive for describing contrast differences between images. The two perceived image contrast models, along with the *SIP*κ differences (Δ*SIP*κ) were modeled for preference using the procedure described by Engledrum.[1]

$$f1(x, x0, a, b) = e^{\frac{|x-x0|^{2/a}}{b}} \tag{15}$$

$$f2(x, x1, c) = \frac{1}{1 + e^{-c(x-x1)}} \tag{16}$$

$$fw(a, b, c, d, x0, x1) = d * f1(x, x0, a, b) * f2(x, x1, c) \tag{17}$$

In *f1(), x* is the percept (perceived contrast in this case) and *x0* is the peak of the image quality scale (preference in this case). The parameters a and b are familiar decay and width parameters. Variables in Eq. (16) control the location, *x1*, and extent, c, of f2(). *Fw*, the product of *f1(), f2()* and scale factor d, is used to empirically represent the non-monotonic, non-linear, image quality versus percept relationship. These results support the use of a perceptual contrast metric in image quality, preference and difference studies.

Modeling Image Preference versus RVP Contrast. Image preference, *fw()*, was modeled for both the actual perceived contrast scale, and the SIP contrast model. Functions *f1()* and *f2()* were generated for the five pictorial images and averaged. The function *fw()* was calculated as the product of the averaged *f1()* and averaged *f2()* and d. Function parameters were optimized for RMS error between *fw()* and the actual image preference scale. From Fig. 18, it is clear on average there is an image independent relationship between modeled image preference and RVP contrast. Parameters used for the *fw()* function are shown in Table IV.

Modeling Image Preference versus SIP Contrast. Image preference, *fw()*, was modeled for both the actual perceived contrast scale, and the SIP contrast model. Functions *f1()* and *f2()* were generated for the five pictorial images and averaged. The function *fw()* was calculated as the product of the averaged *f1()* and averaged *f2()* and d. Function parameters were optimized for rms error between *fw()* and the actual image preference scale. From Fig. 19, it is clear there is an image dependent relationship between modeled image preference and perceived contrast *SIP*κ, which is understandable. The *SIP*κ model is based on single image characteristics. There is no reason to expect images of different subject matter to have similar physical characteristics. At this point it is misleading to draw conclusions from

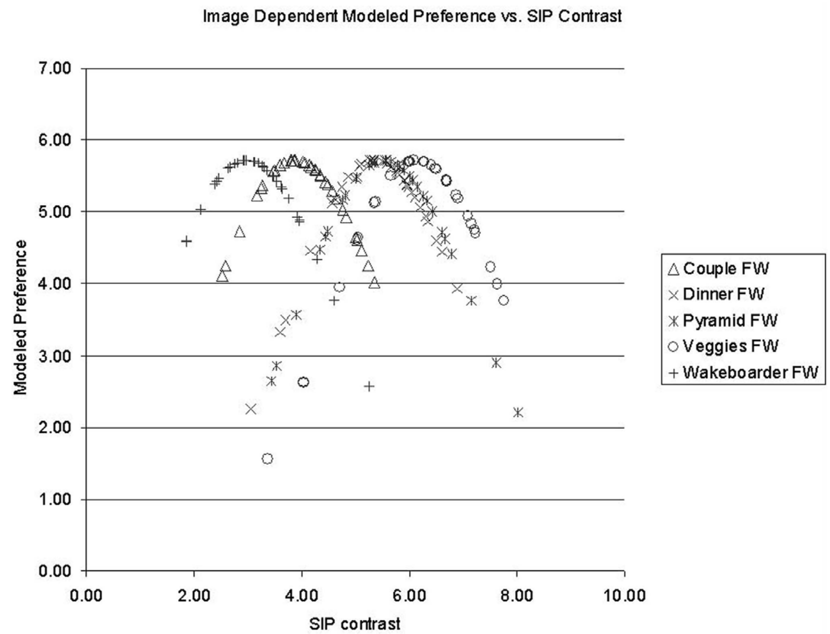

Figure 19. Modeled image preference versus *SIP*κ.

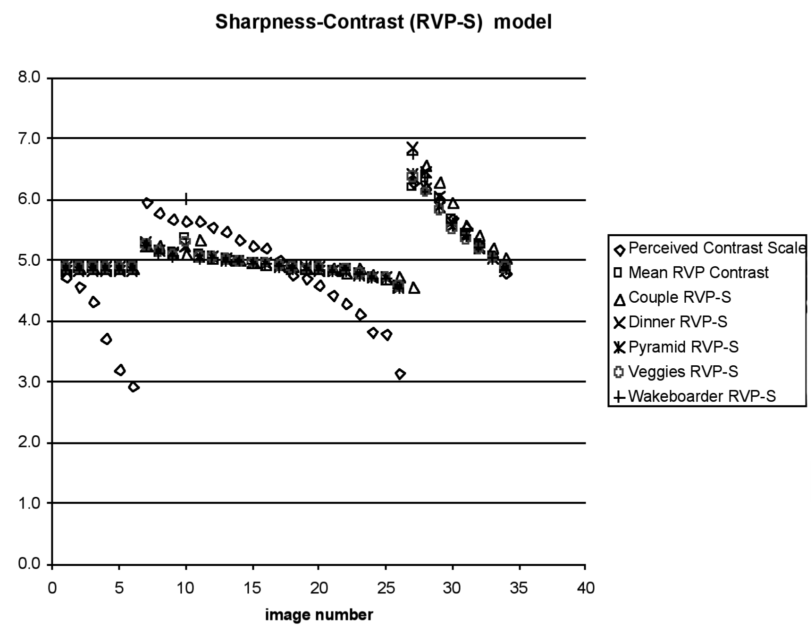

Figure 20. Modeled image preference versus *SIP*κ difference from preferred image.

the image dependent results as to preference between different subject matter images.

Modeling image preference as a function of perceived contrast difference from the most preferred (as shown in Eq. (14)) yielded an image independent relationship (Fig. 20) on average. Given the likeness of the preference curves of Fig. 19, the preference–percept relationship was expected. It is intuitive that preference should decrease as contrast difference from the most preferred image increases. Parameters for preference as a function of SIPκ and SIPκ difference were identical.

Image Preference Modeling Conclusions. The two metrics of perceived image contrast were modeled for image preference. Image independent models were fit for the *RVP*κ model and Δ*SIP*κ metrics. Image dependent results were fit for the *SIP*κ contrast metric. These results ensure that the image preference *fw()* model used for fitting image quality data can be used to model the preference–percept relationship. Fitting image preference as a function of to *RVP*κ illustrates preference can be modeled as a function of image pair characteristics. Fitting image preference as a function of *SIP*κ differ-

TABLE IV. Image Preference Parameters, Modeled from *RVPκ* and *SIPκ*

	RVP contrast	SIP contrast
RMS Chroma	1.12	1.19
RMS Lightness	1.70	1.02
RMS Sharpness	0.65	0.63
Total RMS	2.13	1.69
F1 Parameters		
X0	3.27	4.86
A	0.78	1.57
B	30.96	4.23
F2 Parameters		
X1	3.41	–11.52
C	1.00	1.00
FW Parameters		
D	2.38	5.92

ence illustrates image preference can be modeled as a function of single image characteristics.

Conclusions

Empirical model fitting of perceived contrast data was attempted. In *Reproduction Versus Preferred* (RVP) contrast modeling, image statistics relative to statistics of the most preferred image were found to describe perceived image contrast. The *RVP*κ contrast model enables the description of perceived image contrast relative to the most preferred version of that image independent of image content. In *Single Image Perceived (SIP)* contrast modeling, single image statistics were found to describe perceived image contrast differences between images and the most preferred version of that image, independent of image content. In both cases, the manipulations associated with the greatest model error were manipulated by the histogram equalization. The achromatic manipulation of the histogram equalization was not represented well by the simple metrics used to describe lightness-contrast. This indicates the *RVP*κ and *SIP*κ contrast models presented may be adequate when dealing with simple image manipulations (much like those in image reproduction) but a more robust metric may be necessary when describing images manipulated by various digital imaging tools.

Data from the two metrics of perceived image contrast were modeled for image preference. Image independent models were fit for the *RVP*κ metric and Δ*SIP*κ metric. These results ensure that the image preference *fw()* model used for fitting image quality data can be used to model the preference–percept relationship. Fitting image preference as a function of to *RVP*κ illustrates preference can be modeled as a function of image pair characteristics. Fitting image preference as a function of *SIP*κ difference illustrates image preference can be modeled as a function of single image characteristics.

References

1. H. De Ridder, Naturalness and Image Quality: Saturation and lightness variation in color images, *J. Imaging Sci. Technol.* **40**(6), 487–493, (1996).
2. P. G. Engeldrum, Extending Image Quality Models, *Proc. IS&T's 2002 PICS Conference*, IS&T, Springfield, VA, 2002, pp. 65–69.
3. L. Stroebel, J. Compton, I. Current. and R, Zakia, *Photographic Materials and Processes,* Focal Press, Boston, MA, 1986.
4. P. A. Mlsna, Q. Zhang, J. J. Rodriguez, 3-D histogram modification of color images, *IEEE Trans. Image Processing*, 1015–1018 (1996).
5. J. Tubmlin, J. K. Hodgins and B. K. Guenter, Two methods for display of high contrast images, *ACM Trans. Graphics*, **18**(1), 56–94 (1999).
6. A. J. Calabria and M. D. Fairchild, Perceived image contrast and observer preference I. The effects of lightness, chroma, and sharpness manipulations on contrast perception, *J. Imaging Sci. Technol.* **47**, 479–493 (2003)
7. M. D. Fairchild and E. Pirotta, Predicting the lightness of chromatic object colors using CIELAB, *Color Res. Appl.* **16**(6), 385–393 (1991).