Title: Perceived image contrast and observer preference II. Empirical modeling of perceived image contrast and observer preference data

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Abstract

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* contrast (RVPκ) modeling, image parameters were taken relative to the most preferred version of the image. In *Single Image Perceived contrast* (SIPκ) 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. Although SIP contrast modeling resulted in scales of different magnitudes, differences in SIPκ from the most preferred version of the image fit the perceived image contrast data. SIPκ 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.

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. A means of empirically modeling nonmonotonic image percepts vs. image quality has been proposed[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.[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 contrast should be calculated. Another shortcoming in defining image contrast in terms of a TRC requires an 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 images may have very different perceptual contrasts. 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.

Suppose an experiment is designed where an observer is given two reproductions of an image and asked to select the image he perceives to be of higher contrast. In most likelihood the observer will make his decision based on the two images in front of him with no knowledge of what the original image looks like. It may be that the observer judges the contrast of the image reproductions relative to each other. In this case, the observer may select the higher contrast image based on some mental transformation from one image to the other. Another possibility may be the observer judges the contrast of each image reproduction relative to what he perceives to be his preferred version of the image. In this case, the observer may be judging a hypothetical transformation between each test image and his mental version of the preferred image. Although it may not be possible to determine what observers' ideal or preferred internal representation of an image looks like, it seems quite reasonable that the judgments of perceived contrast for various image manipulations may contribute information relative to the observers' perception of contrast.

The perception of contrast in a single color image is sometimes considered to be a function of the image dynamic range.[4,5] Images with a narrow distribution in dynamic range are thought to be of low contrast; images with a wide dynamic range can be considered of high contrast. Images with histograms low in the midtone regions and high in the light and dark regions can be considered "too contrasty." In digital imaging, histogram explosion and histogram equalization are methods commonly used to utilize the full dynamic range possible and increase contrast. Since these histogram manipulation methods are capable of manipulating perceived contrast, it may be possible to describe contrast based on physical parameters of the image.

There are several important questions one should address when developing a metric for perceived contrast in color images. Should the contrast metric be relative or absolute? Should the metric be image independent? Should achromatic and chromatic versions of the same image have the same contrast? What physical attributes of the image should be incorporated in the contrast metric?

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 is of interest whether these relationships can be modeled empirically based on image characteristics. Physical image characteristics were used to empirically model scales of perceived image contrast. Image preference was modeled as a function of perceived image contrast. Two means of modeling the perceived contrast difference in images were developed.

For the purpose of this research, perceived image contrast has been defined in terms of an image and an observer's most preferred version or internal ideal representation of that image. For these reasons, image parameters have been used relative to the most preferred image for *Reproduction Versus Preferred contrast (RVP*) model fitting. RVP contrast analysis can be thought of as using the most preferred image

(25sc) 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 (SIP) 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, 5 was added to the mean perceived contrast scale values to ensure an all-positive scale. Since the *brainscan* images were judged differently than the pictorial images, all modeling was limited to the pictorial test images. 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 below. Image numbers 1-6 represent chroma-manipulated images, numbers 7-26 represent lightness-manipulated images, and number 27-34 represent sharpness-manipulated images.

Perceived Contrast Modeling

Reproduction Versus Preferred (RVP) Contrast Modeling. It was decided before modeling 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).

Although generating these plots for these RVP parameters was straightforward, determination of the appropriate location on the curve to define as the "straight-line" was not very intuitive. Figure 1a to 1d illustrates 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 Figure 1 is mostly the result of the sharpening manipulations. The most preferred image was an image that had been sharpened. *Unsharp masking* cause increases and decreases in lightness to better define edges. The greater the sharpening amount, the greater the magnitude of edge lightness scaling. This is evident by examining RVP plots of images of higher sharpness-contrast. 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 (red line in Figure 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.

$$RVP\kappa_L = 2.640\kappa_L + 1.863 \qquad (1)$$

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

RVP Chroma-Contrast Modeling. Modeling of the perceived chroma-contrast data was straightforward. The mean pixel-wise image chroma ratio between an image and the preferred-image chroma fit quite well (Equation 2). Chroma-contrast is represented by the variable $RVP\kappa_C$ defined in Equation 3.

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

$$RVP\kappa_C = 2.00\kappa_C + 2.097 \qquad (3)$$

$RVP\kappa_C$ represents RVP contrast from chroma. From Figure 3 it is observed the chroma-contrast is modeled with very little lightness-contrast or sharpness-contrast information.

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 Equation 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.

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

This filter was generated using a gaussian that peaked at the highest frequencies (see Figure 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 ($RVP\kappa_S$).

$$RVP\kappa_S = 1.038\kappa_S + 3.988 \qquad (5)$$

The variable κ_S represents the mean ratio of high-pass lightness images (see Equation 4). In Figure 5 it is shown the sharpness data is 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.

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.

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

Equation 6 was fit to the mean contrast scale minimizing RMS error. The value RVPκ represents RVP contrast.

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.

	Contrast 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

Table 9-II. Image RVPκ models with model parameters and weights.

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

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. 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 the perception of *Reproduction Versus Preferred (RVP) contrast* of an image relative to the most preferred version of that image using metrics of relative lightness, chroma, and sharpness. Modifications were made to the model in an attempt to make it simpler and more intuitive. These modifications sacrificed accuracy in an attempt to achieve purposes of simplicity or intuitiveness.

It is worth noting that this model is based on three parameters the most preferred image based on previous experiments[6]. It was not possible to test every possible combination of reference images and image parameters.

Single Image Perceived (SIP) Contrast. In the previous section, perceived 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 (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 perception-based SIPκ_L model was preferred (Equation 8).

$$\kappa_L = \sigma^2\left(L*\right) \quad (7)$$

$$SIP\kappa_L = 0.914\kappa_L + 3.86 \quad (8)$$

Where 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 SIPκ_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*). All three parameters predicted chroma-contrast relatively well.

$$\kappa_C = \sigma^2\left(C^*_{ab}\right) \qquad (9)$$

$$SIP\kappa_C = 0.118\kappa_C + 2.496 \qquad (10)$$

Since the three chroma statistics tested predicted the scale with equivalently, κ_C is defined as standard deviation of chroma (Equation 9) in for SIPκ_C 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 (Figures 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 (RVPκ_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 (Equation 10) fit the data best and was used as κ_S in Equation 11.

$$\kappa_S = \sigma^2\left(HF_{L*}\right) \qquad (10)$$

$$SIP\kappa_S = 915.251\kappa_S + 4.073 \qquad (11)$$

Figures 12 and 13 indicate the sharpness-contrast metric does influence the lightness-contrast data. The chroma-contrast data appear independent of SIPκ_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 lightness) were regressed to the all-positive linked perceived-contrast scale. Equation 12 was developed to model the perceived contrast of a single image (SIPκ).

$$SIP\kappa = -1.505 + 0.131\kappa_C + 0.151\kappa_L + 666.216\kappa_S \qquad (12)$$

Figures 14 and 15 illustrate the goodness of fit of SIPκ to the mean perceived contrast data. From Figure 14 the image dependence of this model is clearly obvious. There is only one significant outlier noticeable in Figure 15. This outlier is the histogram equalization manipulation. All other manipulations are modeled well.

Images of similar mean perceived contrast have differences in SIPκ, 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 SIPκ weights are shown in Table III.

	Contrast 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

Table III. Image SIPκ with model parameters.

The parameter weights in the SIPκ 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 $1/10000^{th}$ the magnitude of the $SIP\kappa_L$ or $SIP\kappa_C$ terms.

Despite image dependency, the strength of the SIPκ contrast model is the ability to quantify differences in perceived contrast. A difference between image SIPκ from the most preferred image SIPκ models the difference between their corresponding perceived image contrast scale values.

$$C_i - C_p = SIP\kappa_i - SIP\kappa_p = \Delta SIP\kappa \qquad (13)$$

In Equation 13 the perceived contrast scale value (determined previously) of an image is $C_{i,p}$ (subscripted i for image and p for preferred), and the modeled perceived contrast of those same images are $SIP\kappa_{i,p}$ (subscripted similarly). Figures 16 and 17 illustrate these differences are image independent.

Single Image Perceived (SIP) Contrast Summary. SIPκ, an image dependent model of perceived image contrast in a single image was developed based on colorimetric characteristics of a single image (Equation 12). Although the *Single Image Perceived Contrast* (SIPκ) model cannot be used to predict contrast differences between images of different subject matter, contrast differences between images of the same subject matter can be predicted (Equation 13). 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 SIPκ is intuitive since images perceived of equal contrast have a 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 *Reproduction Versus Preferred* (RVP) contrast. This attempt was to determine if the perception of image contrast in a single image can 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 RVPκ contrast model (Equation 6) enables the description of 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 contrast metric. *Single Image Perceived (SIP) 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 (SIPκ) was fit in which similar manipulations of different test images were proportional. An image independent model of SIPκ difference (Equation 13) from the most preferred image was developed. Differences in SIP contrast can predict similar contrast manipulations performed on images of different subject matter.

Image Preference Modeling.

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

$$f1(x, x0, a, b) = e^{-\frac{|x - x0|^{2/a}}{b}} \qquad (14)$$

$$f2(x, x1, c) = \frac{1}{1 + e^{-c(x - x1)}} \qquad (15)$$

$$fw(a, b, c, d, x0, x1) = d * f1(x, x0, a, b) * f2(x, x1, c) \qquad (16)$$

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 Equation 15 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 vs. percept relationship. These results support the use of a perceptual contrast metric in image quality, preference and difference studies.

Modeling Image Preference vs. RVP Contrast. Image preference, *fw()*, was modeled for both the actual perceived contrast scale, and the RVP 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 Figure 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 vs. 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 Figure 19, it is clear there is an image dependent relationship between modeled image preference and perceived contrast SIPκ, which is understandable. The SIPκ 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 the image dependent results as to preference between different subject matter images.

Modeling image preference as a function of contrast difference from the most preferred (as shown in Equation 13) yielded an image independent relationship (Figure 20) on average. Given the likeness of the preference curves of Figure 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 image contrast were modeled for image preference. Image independent models were fit for the RVPκ and SIPκ difference metrics. Image dependent results were fit for the SIPκ 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 RVPκ illustrates preference can be modeled as a function of image pair characteristics. Fitting image preference as a function of SIPκ difference 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 the perception of image contrast. The RVPκ contrast model enables the description of 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 contrast differences between images and the most preferred version of that image independent of image content.

The two metrics of image contrast were modeled for image preference. Image independent models were fit for the RVPκ metric and SIPκ difference 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 RVPκ illustrates preference can be modeled as a function of image pair characteristics. Fitting image preference as a function of SIPκ difference illustrates image preference can be modeled as a function of single image characteristics.

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Figure 1. Image L* channel shown as a function of the most preferred image (25sc) L* channel. The mean output L* is shown in red. Minimum and maximum output L* shown in black.

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 RVPκ_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 RVPκ_S calculations.

Figure 5. Perceived image contrast scale with modeled image RVPκ_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 vs. actual contrast scale.

Figure 8. Perceived image contrast scale with modeled image SIPκ_L for all pictorial images.

Figure 9. Mean perceived image contrast scale with modeled image SIPκ_L.

Figure 10. Perceived image contrast scale with modeled image SIPκ_C for all pictorial images.

Figure 11. Mean perceived image contrast scale with modeled image SIPκ_C.

Figure 12. Perceived image contrast scale with modeled image SIPκ_S for all pictorial images.

Figure 13. Mean perceived image contrast scale with modeled image SIPκ_S.

Figure 14. Perceived image contrast scale with modeled image SIP$\kappa$for all pictorial images.

Figure 15. Mean perceived image contrast scale with modeled image SIPκ for all pictorial images.

Figure 16. SIPκ difference vs. image number.

Figure 17. Mean SIPκ contrast difference vs. actual mean perceived contrast scale difference.

Figure 18. Mean modeled RVP image preference vs. actual image preference scale.

Figure 19. Modeled image preference vs. SIPκ.

Figure 20. Modeled image preference vs. SIPκ difference from preferred image.

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 number 27-34 represent sharpness-manipulated images.

Table IV. Image preference parameters, modeled from RVPκ and SIPκ

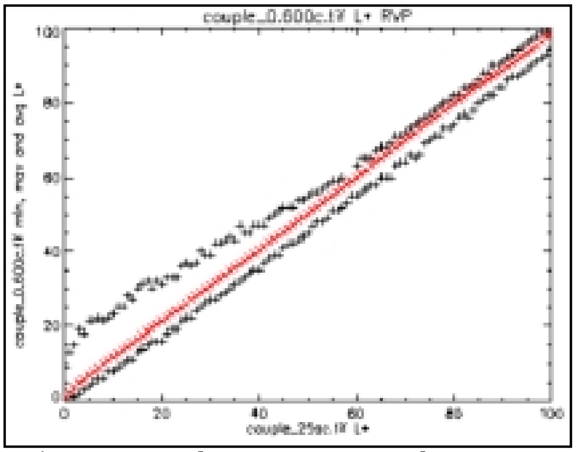

Figure 1a. couple 0.600c L* vs. couple 25sc L*

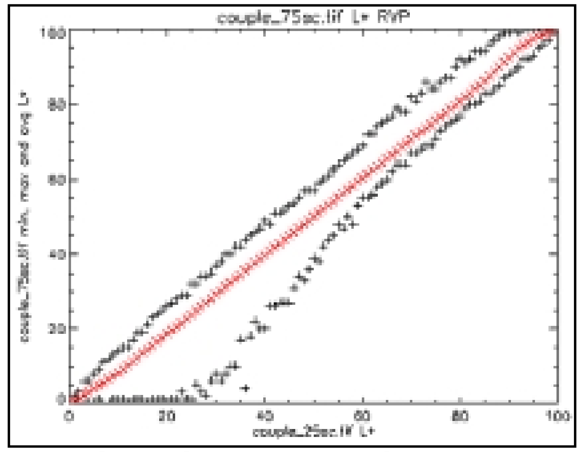

Figure 1b. couple 75sc L* vs. couple 25sc L*

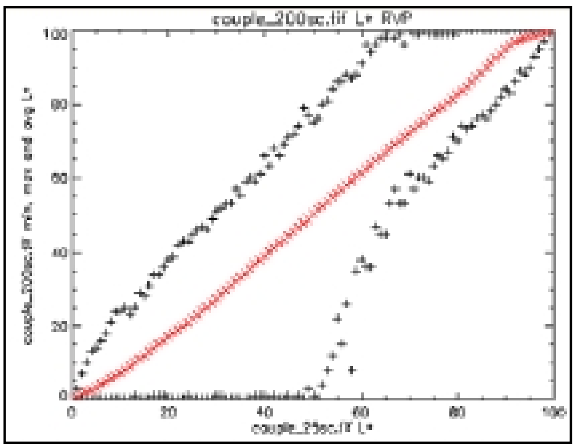

Figure 1c. couple 200sc L* vs. couple 25sc L*

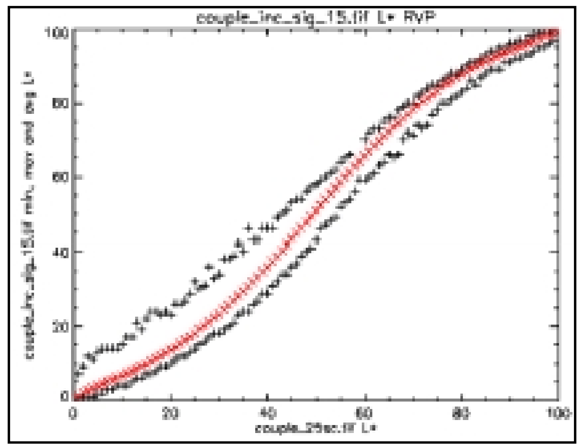

Figure 1d. couple inc_sig_15 L* vs. couple 25sc L*

Figure 1. Image L* channel shown as a function of the most preferred image (25sc) L* channel. The mean output L* is shown in red. Minimum and maximum output L* shown in black.

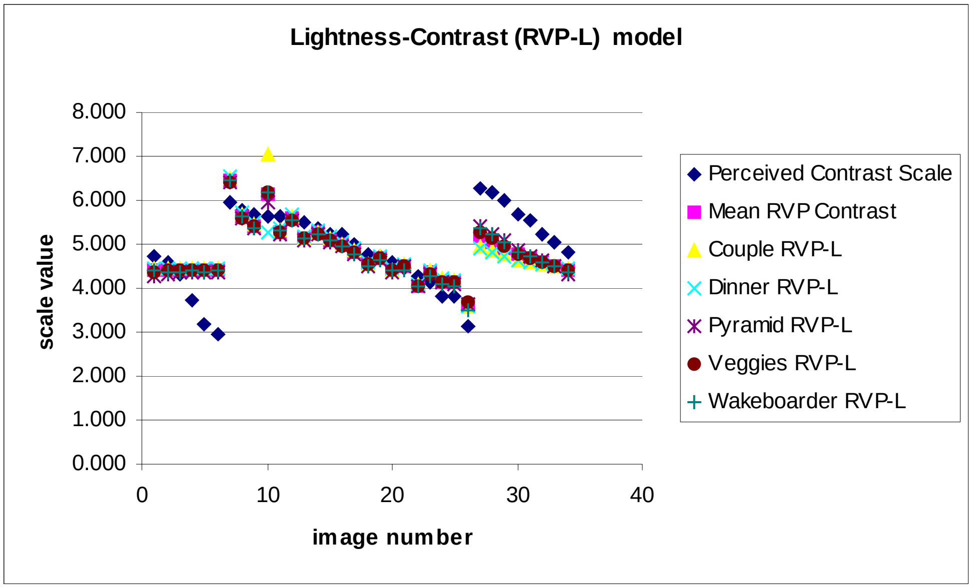

Figure 2. Perceived image contrast scale with modeled image RVPκ_L. Images are numbered in order of decreasing contrast for chroma-contrast (Image numbers 1-6), lightness-contrast (Image numbers 7-26), and sharpness-contrast (Image numbers 27-34)

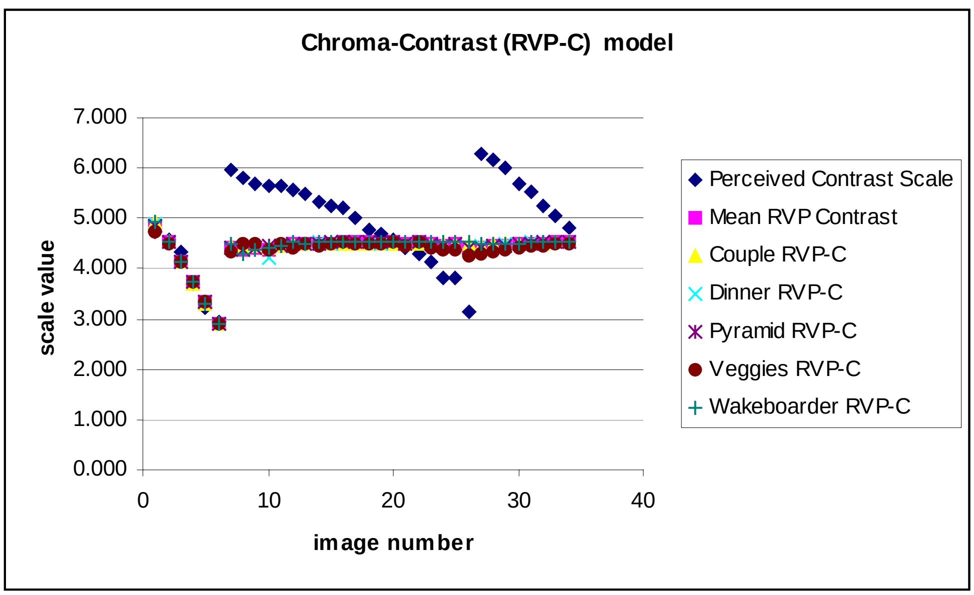

Figure 3. Perceived image contrast scale with modeled image RVPκ_C. Images are numbered in order of decreasing contrast for chroma-contrast (Image numbers 1-6), lightness-contrast (Image numbers 7-26), and sharpness-contrast (Image numbers 27-34).

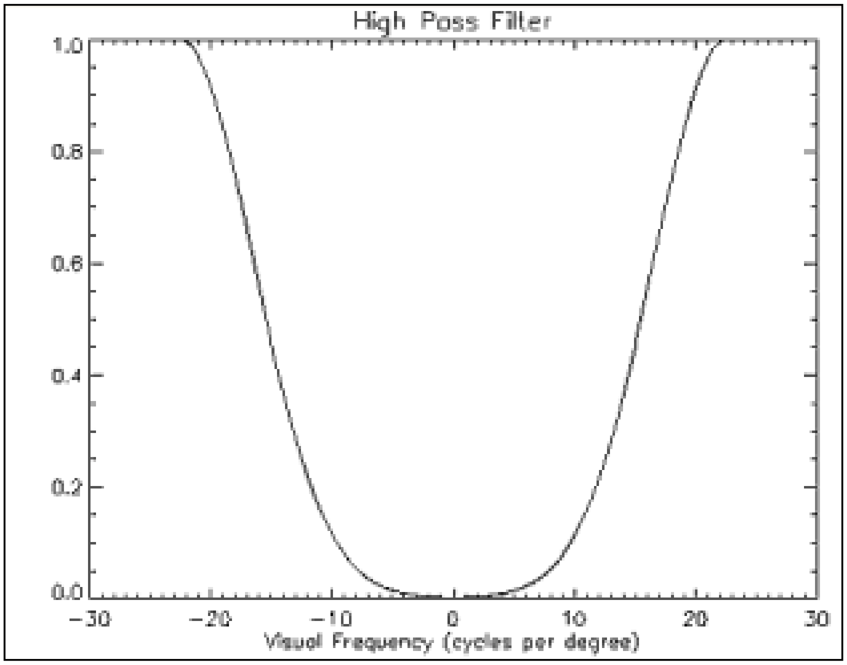

Figure 4. High-Pass Filter used for RVPκ$_S$ calculations.

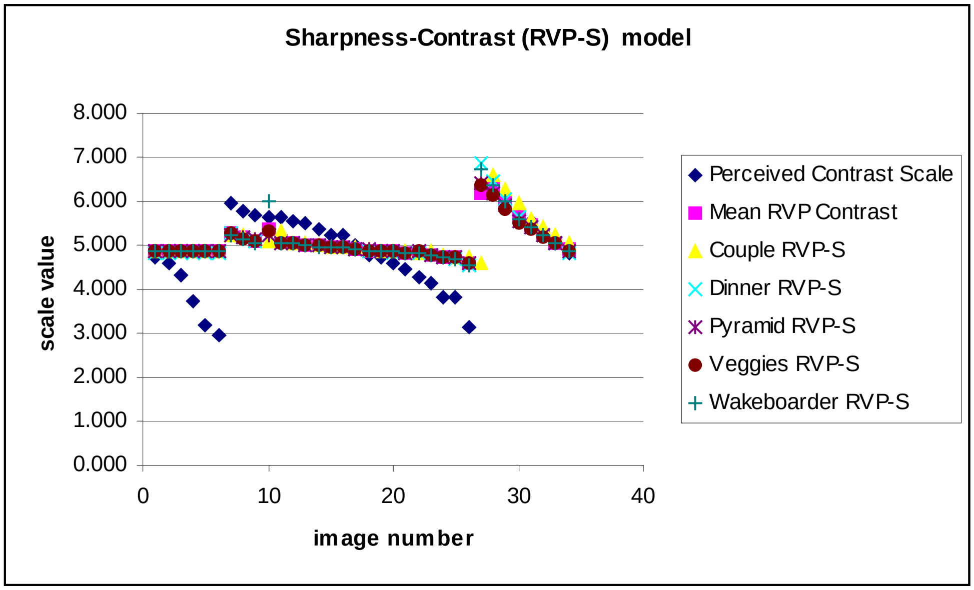

Figure 5. Perceived image contrast scale with modeled image RVPκ$_S$. Images are numbered in order of decreasing contrast for chroma-contrast (Image numbers 1-6), lightness-contrast (Image numbers 7-26), and sharpness-contrast (Image numbers 27-34).

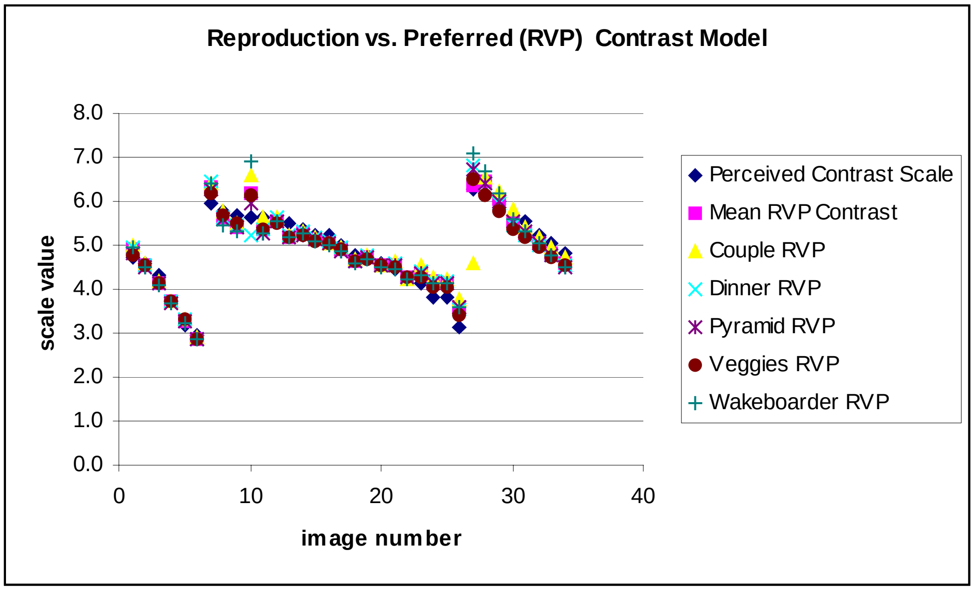

Figure 6. Perceived image contrast scale with modeled image RVPκ.

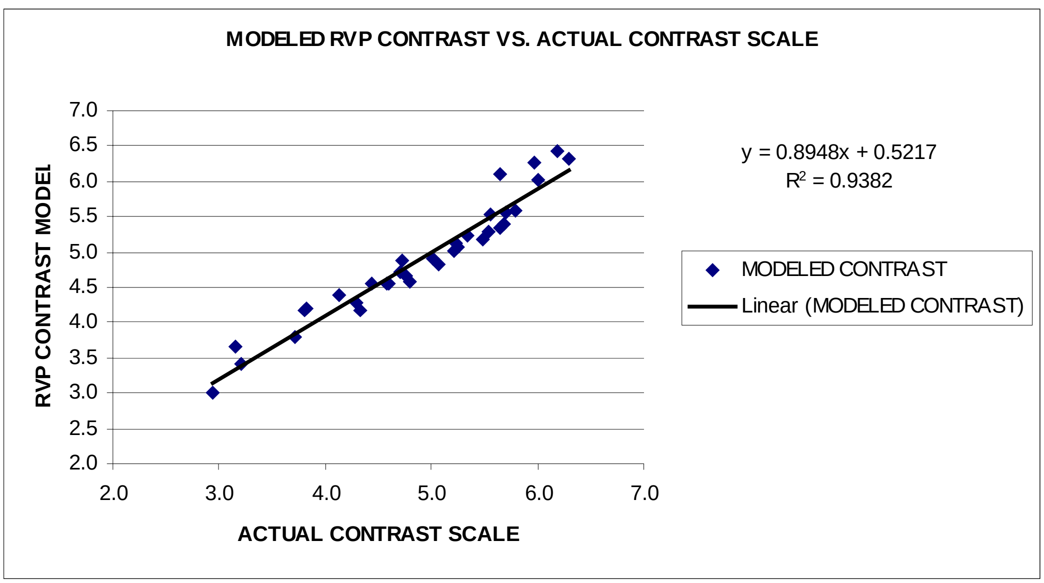

Figure 7. Mean Modeled RVP contrast scale vs. actual contrast scale.

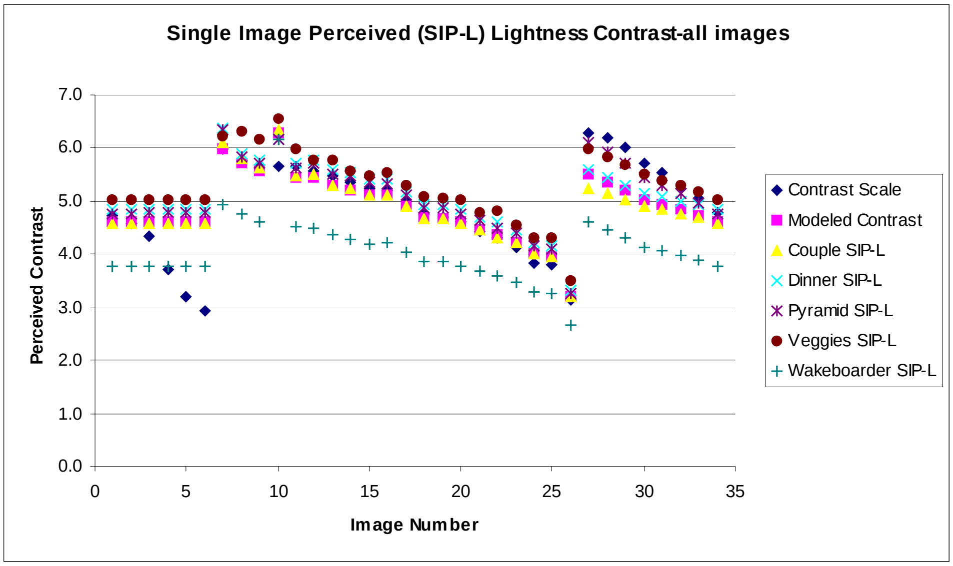

Figure 8. Perceived image contrast scale with modeled image SIPκ_L for all pictorial images.

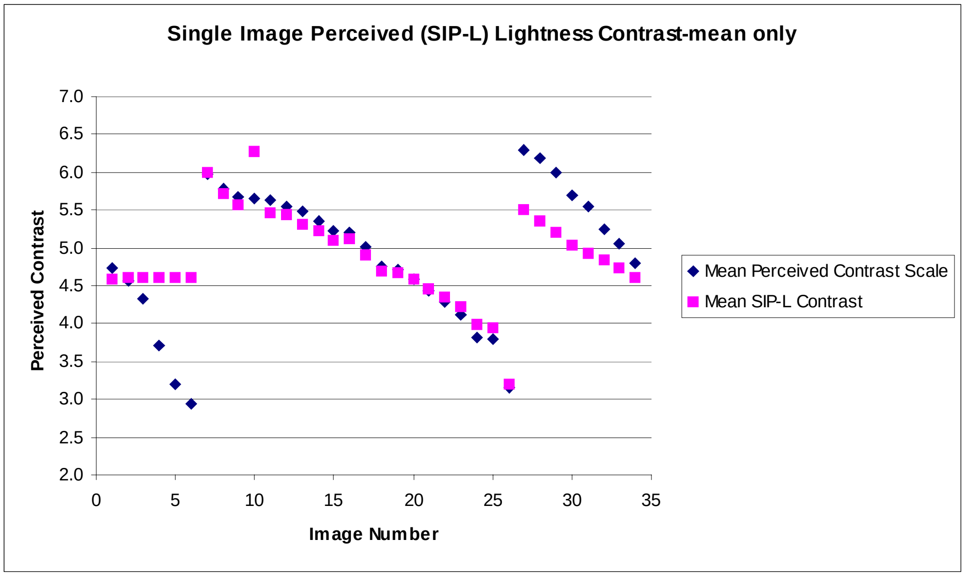

Figure 9. Mean perceived image contrast scale with modeled image SIPκ_L.

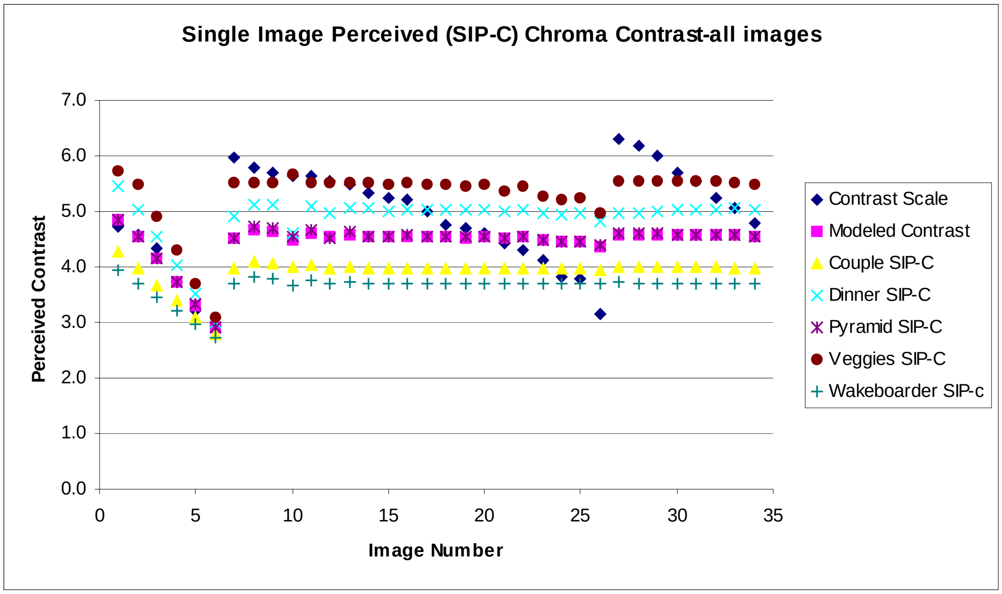

Figure 10. Perceived image contrast scale with modeled image SIPκ_C for all pictorial images.

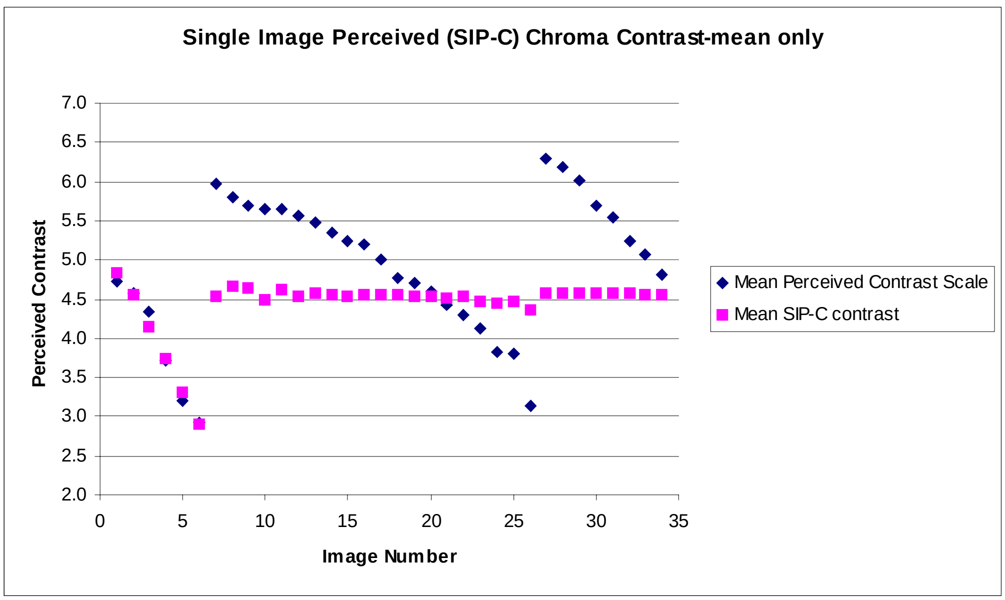

Figure 11. Mean perceived image contrast scale with modeled image SIPκ_C.

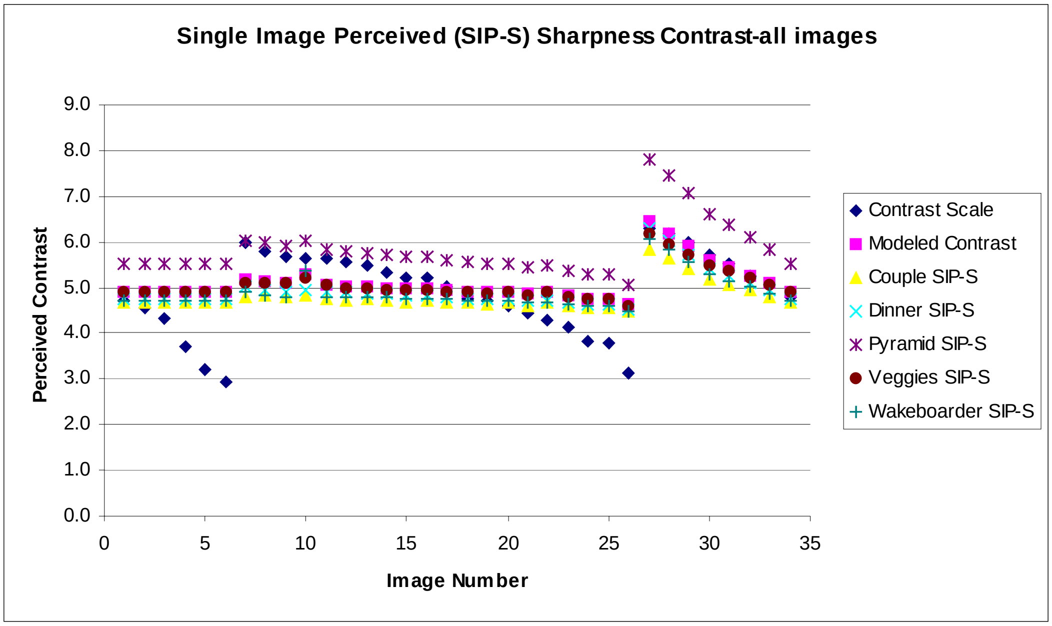

Figure 12. Perceived image contrast scale with modeled image SIPκ_S for all pictorial images.

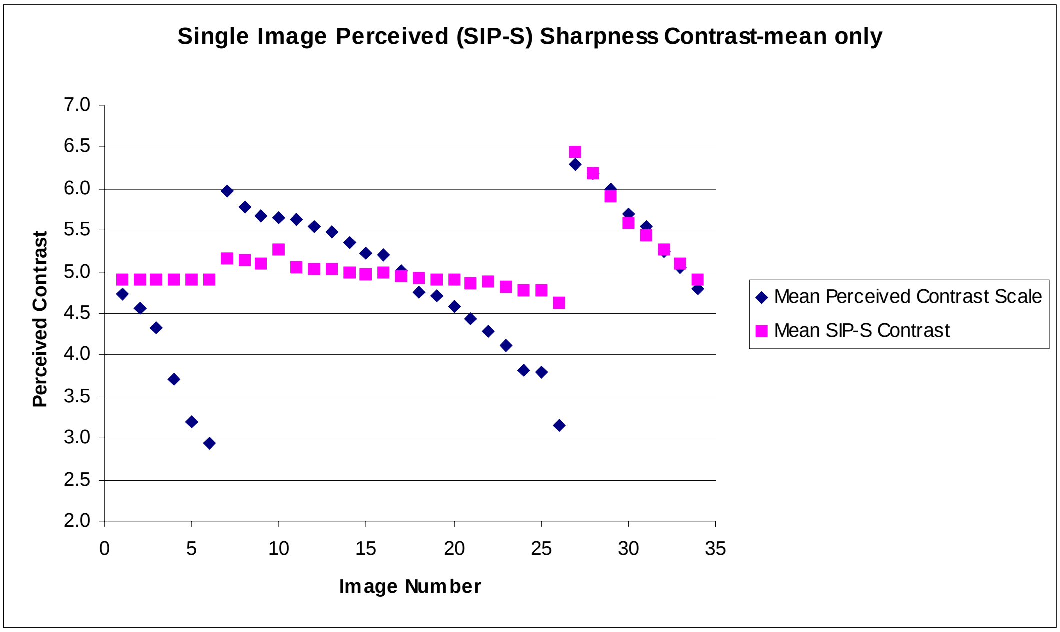

Figure 13. Mean perceived image contrast scale with modeled image SIPκ_S.

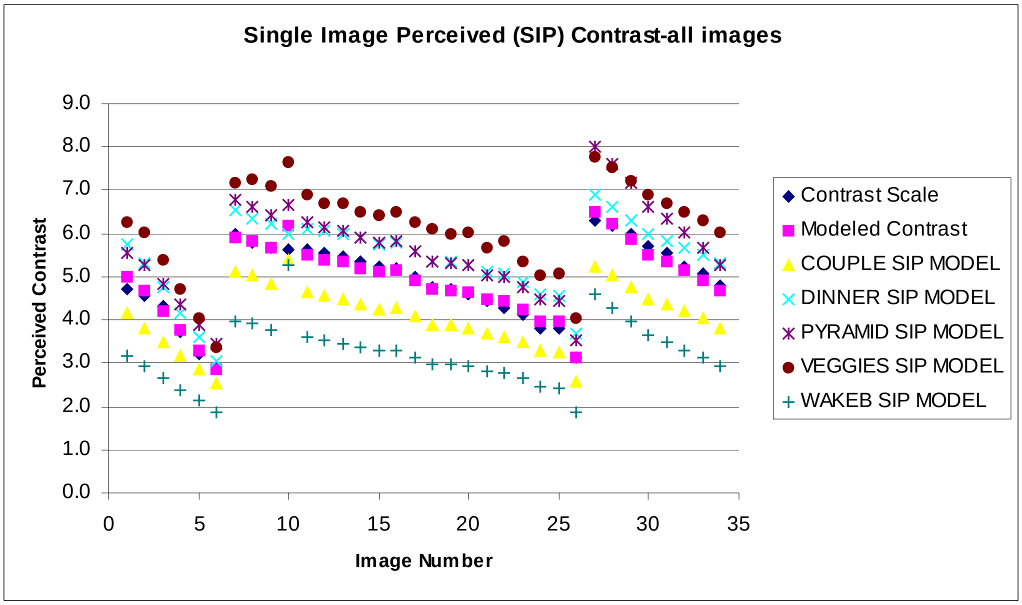

Figure 14. Perceived image contrast scale with modeled image SIPκ for all pictorial images.

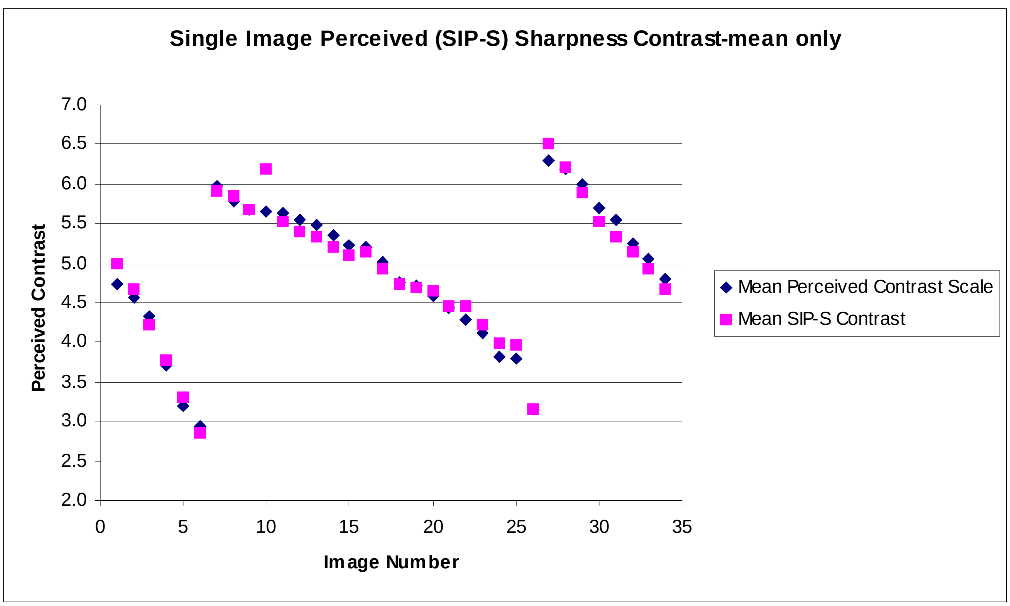

Figure 15. Mean perceived image contrast scale with modeled image SIPκ for all pictorial images.

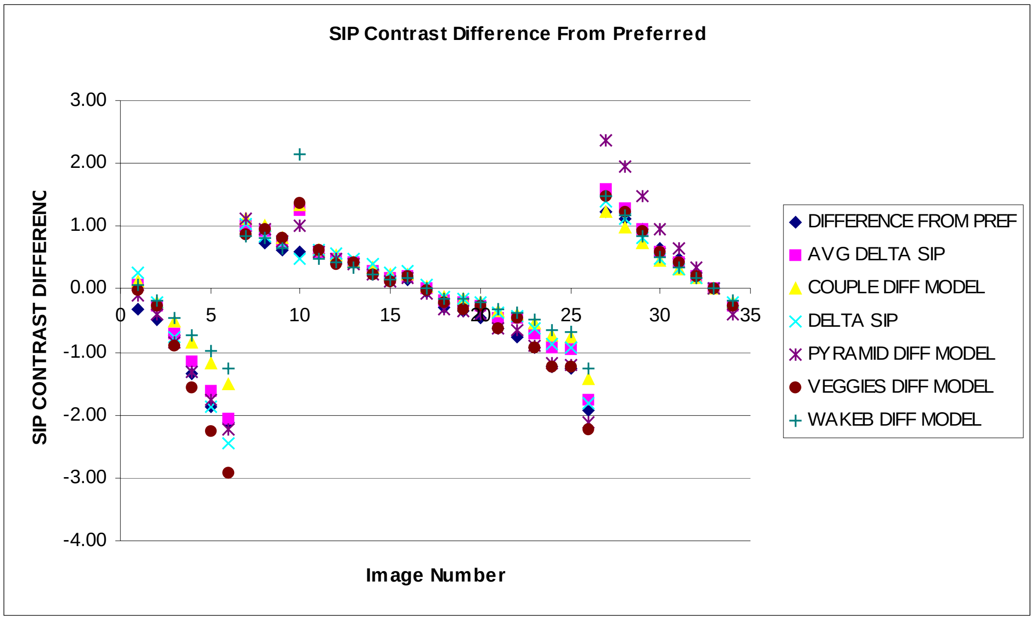

Figure 16. SIPκ difference vs. image number.

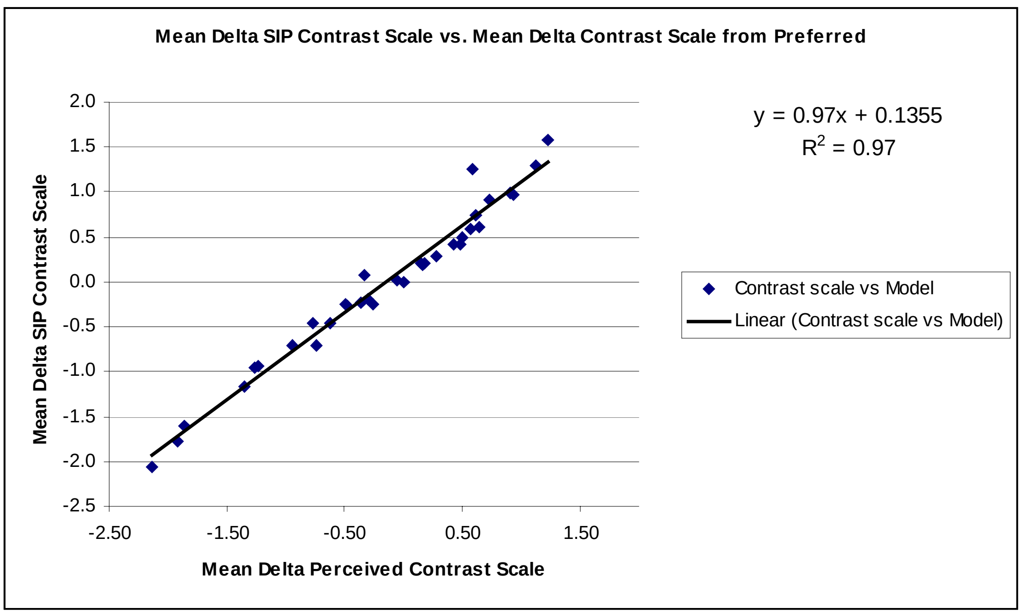

Figure 17. Mean SIPκ contrast difference vs. actual mean perceived contrast scale difference.

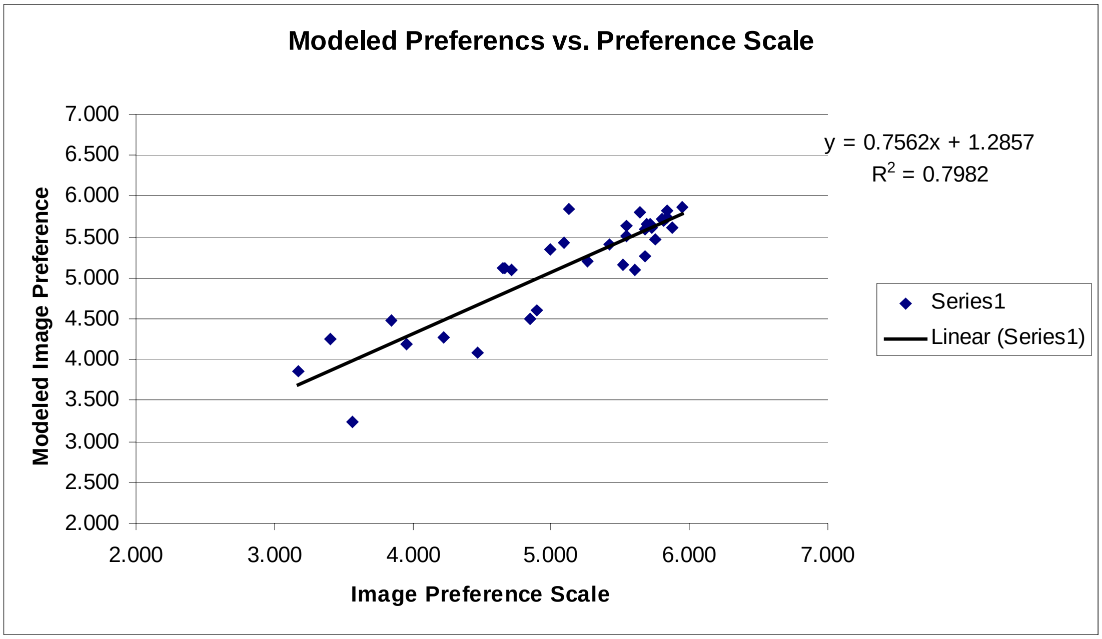

Figure 18. Mean modeled RVP image preference vs. actual image preference scale.

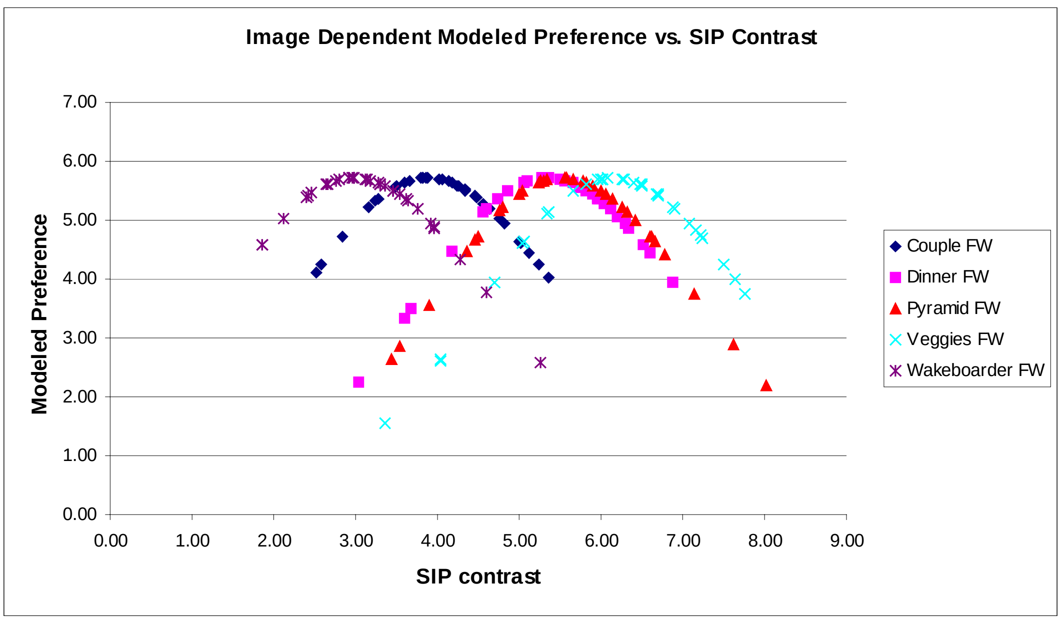

Figure 19. Modeled image preference vs. SIPκ.

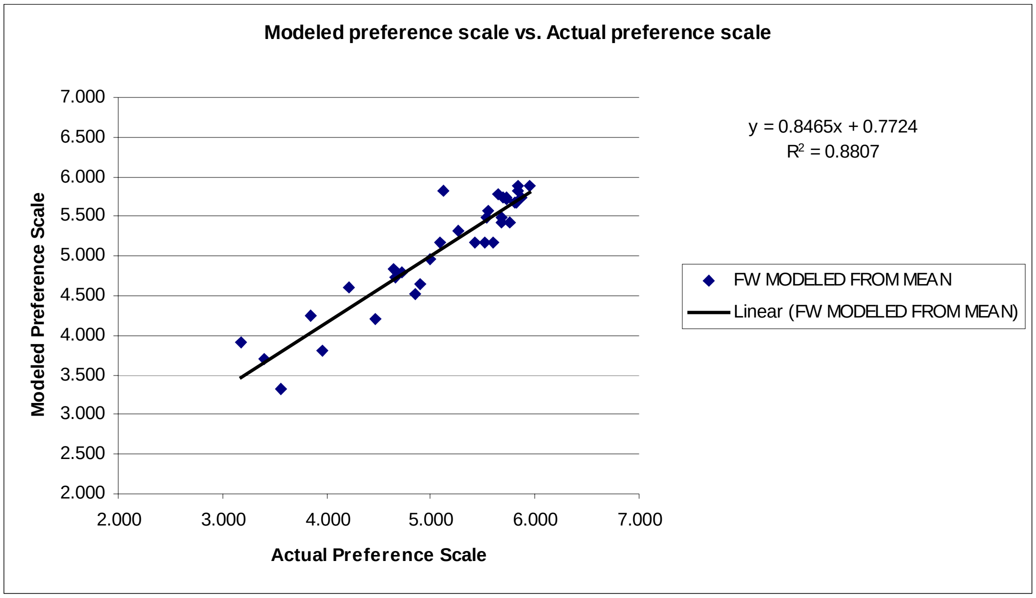

Figure 20. Mean modeled SIP image preference vs. actual image preference scale.

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	gma_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	gma_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	gma_0.950
26	gma_0.900
27	250sc
28	200sc
29	150sc
30	100sc
31	75sc
32	50sc
33	25sc
34	0sc

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 number 27-34 represent sharpness-manipulated images.

	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

Table IV. Image preference parameters, modeled from RVPκ and SIPκ