Color Image Fidelity Assessor*

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Abstract

In this paper, we describe the Color Image Fidelity Assessor (CIFA) which extends Taylor et al's achromatic IFA. The CIFA is a visual model that assesses perceived image fidelity in three channels: luminance and two opponent chromatic channels: red-green and blue-yellow. We introduce a novel color descriptor that we call chromatic difference to measure the spatial interaction between colors in the chromatic channels. A set of discrimination experiments is presented that use stimuli based on receptor fields observed in the mammalian visual system. Difference thresholds measured in these experiments are incorporated in the CIFA look-up tables. Finally, we show an example illustrating predictions of CIFA for a hue-distorted image.

1. Introduction

Perceived image fidelity is a measure of the visual similarity between two images. Two images are considered to be visually identical if no difference between them can be detected by human observers. Since the goal of many imaging systems and image processing algorithms is visually lossless reproduction, it is very important to be able to evaluate the visual differences accurately. The intent of an image fidelity assessor is to serve this purpose without actual human observers and to ultimately yield information that could be provided to the designer to improve an imaging system or processing algorithm.

One simple approach is to compute root-mean-squared error (RMSE) between the original image and the reproduction, in an appropriate space, such as CIE $L^*a^*b^*$. However, it is well known that this measure provides an inadequate estimate of perceived image fidelity. A more logical approach is to use a visual model which incorporates the known properties of the structure and functioning of the human visual system.

The image fidelity assessor (IFA) proposed by Taylor et al[1] is one of the many models for measuring perceived achromatic image fidelity[2,3] that has attempted to incorporate the results from electrophysiological and psychophysical experiments. This model was strongly in uenced by Daly's Visual Difference Predictor[2] (VDP) and Lubin's Visual Discrimination Model[3] (VDM). The main feature that distinguishes the achromatic IFA from the VDP or VDM is its ability to avoid an input/output mismatch in the model[1,4].

In this paper, we develop a color image fidelity assessor (CIFA) based on Taylor et al's achromatic IFA. The extension involves adding two opponent channels: red-green (R-G) and blue-yellow (B-Y). Properties of these channels agree with the properties of the opponent channels in the human visual system as described by Hurvich and Jameson[5]. The CIFA operates in a way that is similar to most visual models for image fidelity assessment. It accepts two images and several viewing parameters as the input and produces a set of probability maps as the output. At each pixel, these maps predict the probability that a human observer would notice a difference between the two input images in the luminance, red-green, or blue-yellow channels.

In 1998, Jin el al proposed a color image fidelity assessor called the Color Visual Difference Model[6] (CVDM). It is a color extension of VDP based on spatial CIE $L^*a^*b^*$ model[7]. Conceptually, this model is similar to our CIFA. Both models use opponent-color coordinates, and are color extensions of achromatic visual models that attempt to build from the results of physiological and psychophysical experiments. There are, however, several differences between the two models. The first difference is related to the input/output mismatch. The CIFA was designed to more closely link the structure of the model and the psychophysical data used by the model. Second, the CIFA employs novel spatial opponent features to characterize the spatial interaction of colors both in analyzing the images to be compared and in creating physical stimuli for the psychophysical experiments. Third, the CIFA uses normalization of chromatic responses to remove the dependency on the luminance level in these channels. This normalization process not only simplifies the parameter space needed to be explored in our psychophysical experiment; it also reduces the dimension of the psychometric look-up table in the

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chromatic IFAs.

This paper is organized as follows. In Sec. 2 we introduce a novel spatial opponent feature called chromatic difference. In Sec. 3 we describe the structure of the CIFA. In Sec. 4 we describe a psychophysical experiment designed to determine parameters within the chromatic IFAs. In Sec. 5 we present results of a simulation experiment in which the CIFA was applied to an image with hue-distortion. Sec. 6 presents our conclusions.

2. Chromatic Difference

Without loss of generality, we assume that all images to be compared are calibrated to the CIE *XYZ* space. The R-G and B-Y opponent responses can be computed from *XYZ* as follows[7]:

$$\begin{bmatrix} O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 0.449 & -0.290 & 0.077 \\ 0.086 & -0.590 & 0.501 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}; \qquad (1)$$

Here, O_2 is the opponent response in the R-G channel, O_3 is the opponent response in the B-Y channel (O_1 in our model is equivalent to luminance as measured by Y).

Next, we normalize O_2 and O_3 as follows:

$$(o_2, o_3) = (O_2/Y, O_3/Y). \qquad (2)$$

Here, (o_2, o_3) are the normalized opponent responses in the R-G and B-Y channels. We refer to (o_2, o_3) as the R-G and B-Y opponent chromaticities. The normalized channels (o_2, o_3), unlike the unnormalized channels (O_2, O_3), are insensitive to luminance changes, and thus provide a more adequate representation of chromaticities.

It is known that the visual system is sensitive to contrast of luminance rather than luminance itself. In this paper, we use the luminance contrast definition from Taylor et al[1] for the achromatic channel in CIFA. This definition is a generalization of Michelson contrast for complex images. For chromatic channels, we introduce a novel color descriptor that we call *chromatic difference*. It is intended to play the same role as luminance contrast in the achromatic response. A chromatic difference in the R-G (c_2) or B-Y channel (c_3) is computed as:

$$c_i = (o_i^{\max} - o_i^{\min})/2 \qquad i = 2, 3. \qquad (3)$$

By definition, it is a measure of the chromaticity variation from the average chromaticity of a surrounding area in a given channel (R-G or B-Y).

In the next section, we describe the structure of the CIFA and how it transforms two complex images into units of localized chromatic difference and luminance contrast. These units are then converted into probability maps based on thresholds measured in psychophysical experiments.

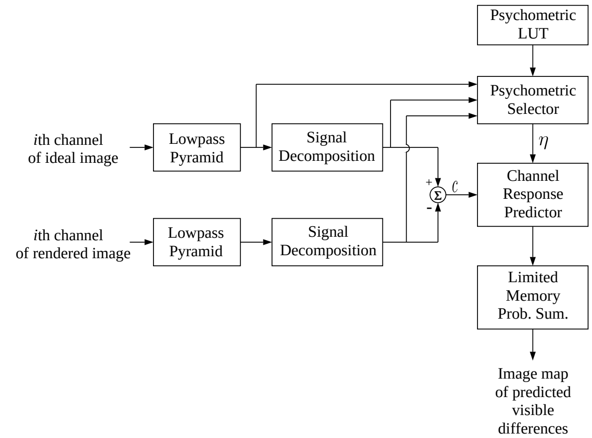


Figure 1: *Block diagram of the Image Fidelity Assessor.*

3. The Color Image Fidelity Assessor

The CIFA is a color extension of the achromatic IFA proposed by Taylor et al[1]. It consists of three components: an achromatic IFA and two chromatic IFAs, namely the R-G IFA and the B-Y IFA. To evaluate perceived image fidelity between two images, both images are first transformed to the opponent-color representation described in Eq. (1) of Sec. 2. The image pair in each opponent channel is then processed by the corresponding IFA to provide the probability map that a human observer will see the differences between the two images along the given opponent axis.

Figure 1 shows the block diagram of each IFA (luminance, R-G, or B-Y). The main difference between the achromatic IFA and the chromatic one lies in the signal decomposition stage and the psychometric look-up tables (LUT). In the chromatic IFAs, the luminance contrast employed in the achromatic IFA is replaced by the chromatic difference introduced in Sec. 2.

To compare images in a given opponent axis, the pair of images are first processed by a *lowpass pyramid* to generate a multiresolution pyramid. Note that for chromatic IFAs the normalization (Eq. (2)) is performed in this stage as well. The *signal decomposition* then transforms these pyramid images into a set of orientation-specific contrast images whose units match the units used in our psychophysical experiments. Based on the visual channel being processed and the image content, the *psychometric selector* chooses the appropriate psychophysical results from the LUT and interpolates them when it is necessary. The *channel response predictor* then applies these psychophysical results to convert the difference between contrast images to probability maps for each channel. The *limited memory probability summation* combines probability maps across visual channels (resolution,orientation) to produce the final probability map, which indicates the probability of seeing a difference between the two input images at each spatial location along a given perceptual axis.

4. Thresholds in Chromatic Difference Discrimination

In the chromatic IFAs, the image is decomposed into a set of visual channels whose responses are a function of thresholds measured in the psychophysical experiments. Since each visual channel is supposed to model the responses of neurons which are highly selective in spatial position, spatial frequency, and orientation, thresholds that are used in the chromatic IFAs should be obtained with stimuli whose spatial properties are localized with respect to those factors as well. In our experiment, this was done by using physiologically motivated Gabor patches[1].

4.1. Method

Isoluminant Gabor patches were generated on a calibrated 24-bit color monitor. Each stimulus consisted of a background color, a reference Gabor patch, and a test Gabor patch (see Fig. 3). The background was a uniform field with color (Y, o_2, o_3), where Y was fixed to 6.89 cd/m^2 (5 lux) in all sessions.

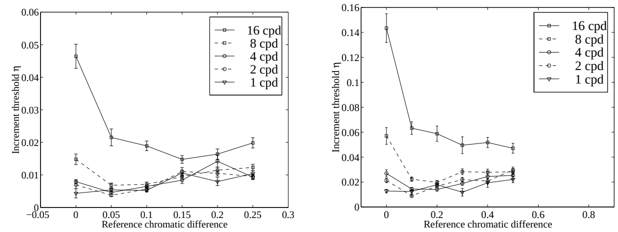
When the R-G opponent channel was tested, the value of o_2 was called the mean chromaticity level for that session. The value of o_3 was chosen so that our monitor could display as large a variety of Gabor patches as possible. Similar idea was implemented, when the B-Y opponent channel was tested. Six background colors were selected in this fashion: three for the R-G channel and three for the B-Y channel.

Once a background color was chosen, the Gabor patches were created by varying the values along the opponent axis to be tested while keeping the other two axes constant.

For each session, eight test patches with different levels of chromatic difference were prepared. The chromatic difference of each test patch was slightly above that of the reference patch. A fixation cross was at the center of the uniform color background throughout the session. Each trial was initiated by pressing the middle mouse button. The reference patch and one of the test patches were then presented at a horizontal eccentricity of 2.5 cycles to either side of the fixation cross. Each test patch was presented 25 times. The test patches were presented in random order; and the side of presentation (left vs. right) for the test and reference patches was randomized as well.

The subject was asked to indicate which patch had lower chromatic difference from the background. The stimuli were displayed until the subject responded. After each incorrect response, an auditory feedback was provided. The results were processed using probit analysis.

Chromatic difference increment thresholds were measured for spatial frequencies 1, 2, 4, 8, and 16 cpd under six adaptation chromaticity levels.



(a) (b)

Figure 2: Discrimination thresholds as a function of reference chromatic difference for subject WW measured along the R-G and B-Y axis when (a) the mean R-G chromaticity level is 0.2 and (b) the mean B-Y chromaticity level is 0.2

4.2. Results and Discussions

Figures 2a and 2b show the discrimination thresholds measured using isoluminant Gabor patches modulated along R-G or B-Y dimension under one of the six background colors, respectively. These curves describe the sensitivity of the human visual system along the R-G or B-Y axis.

From Fig. 2, we see that the threshold is approximately constant in most conditions. The thresholds at frequency 16 cpd are substantially higher compared to other frequencies. This is consistent with prior results[8,9] indicating that the R-G and B-Y channel function like low-pass filters. The threshold is insensitive to the reference chromatic difference (except when it is zero) and to the mean chromaticity level. This constancy of threshold suggests that the normalized opponent channels used here (o_2, o_3) are psychologically plausible. Furthermore, this constancy allows us to reduce the number of parameters characterizing the sensitivity of the human visual system in the R-G and B-Y channels.

5. Simulation Results

Figure 4 show an example of the CIFA applied to a complex image. In this figure, we distorted the colors of the original image by changing the hue. The distorted image appear greenish compared to the original. In particular, the yellow around the body of the parrot in the left appears brighter and more greenish in the distorted image. This agrees with the predictions of the luminance and R-G IFAs. The color around the head of the parrot in the right appears less red in the distorted image. The R-G IFA predicts that, too.

6. Conclusion

In this paper, we developed a human visual model for a color image fidelity assessor. The CIFA extends Taylor el al's achromatic IFA to color. Similar to Taylor el al's work, our model attempts to combine the results of electrophysiological and psychophysical experiments for measuring perceived image fidelity. We designed a psychophysical experiment, the results of which can be applied directly to our model. By doing so, we have kept a consistency between the model and the psychophysical data that are used in the model. As part of our development, we derived a novel color descriptor that can be used to describe efficiently the color percept of the human visual system. We applied the CIFA to several examples[4] for a wide range of image contents and distortion types. From informal visual inspection, we see that the CIFA makes predictions that are similar to what a human observer perceives. In general, from our simulations, we conclude that the CIFA provides good predictions over a wide range of distortion types.

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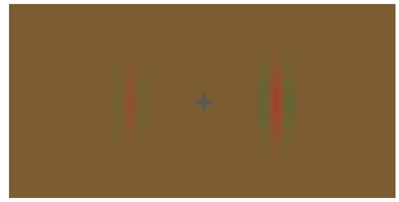

Figure 3: *Sample stimulus of a trial in the chromatic difference discrimination experiment*

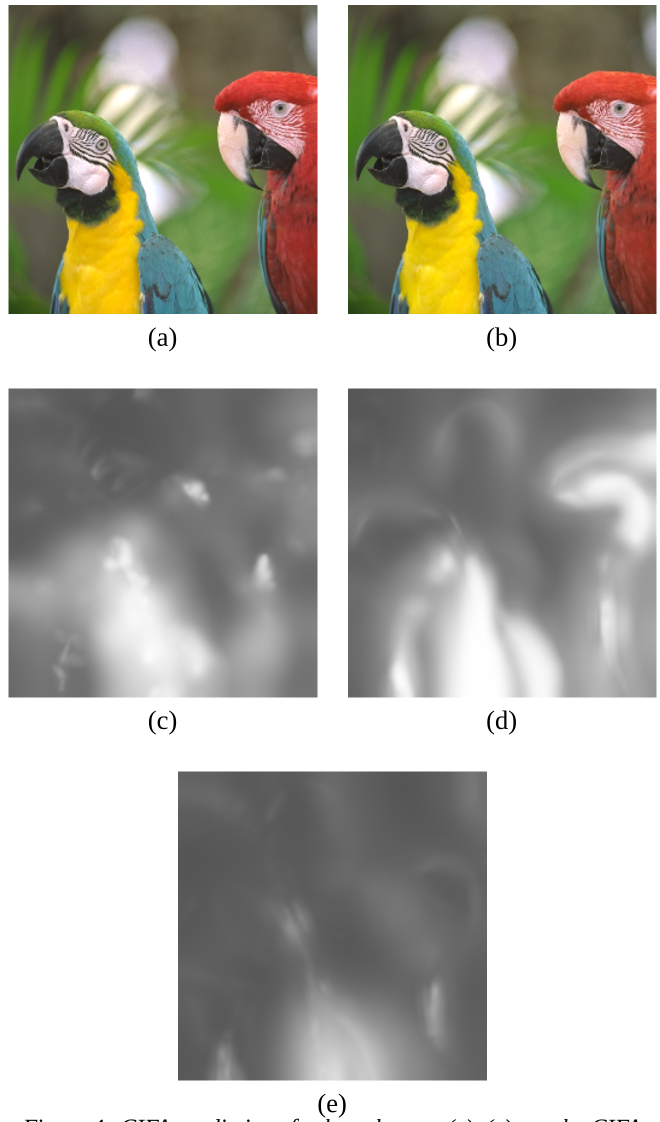

Figure 4: *CIFA predictions for hue change. (c)–(e) are the CIFA probability maps for (a) the* parrots *image compared with (b) the* parrots *image distorted by changing the hue. The probability maps (c), (d), and (e) correspond to the probability of visible differences in luminance, R-G, and B-Y channels, respectively. The viewing distance in the CIFA was 15 times image height.*