A SPATIAL EXTENSION OF CIELAB FOR DIGITAL COLOR IMAGE REPRODUCTION *

Xuemei Zhang and Brian A. Wandell
Department of Psychology, Stanford University
Stanford, CA 94305

1 Abstract

We describe a spatial extension to the CIELAB color metric that is useful for measuring color reproduction errors of digital images. To compute the error, digital color images are spatially filtered using a pattern-color separable method and then converted into the CIELAB representation. Over patterned regions of the image, the reproduction errors measured using the spatial extension of CIELAB correspond to perceived color errors better than errors computed without the spatial extension. Over uniform spatial regions of the image, errors computed with the extension are equal to errors computed using the standard CIELAB formulae.

2 Introduction

The CIELAB system (CIE 1978) is an important international standard for measuring color reproduction errors. This system was created in a period when most color reproduction applications were concerned with matching large uniform colored areas. Hence, the CIELAB system was tested against data from color appearance judgments of large uniform fields.

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With the growth of digital color imaging, many applications have been developed to process real images. However, most real images are not made up of large uniform fields. Many psychophysical studies show that discrimination and appearance of small-field or fine-patterned colors differ from similar measurements made using large uniform fields (Noorlander & Koenderink, 1983; Poirson & Wandell, 1993, 1995; Bäuml and Wandell, 1996). Therefore, applying CIELAB to predict local color reproduction errors in patterned images does not give satisfactory results. For example, when we compare a continuous-tone color image with a halftone version of the image, a point-by-point computation of the CIELAB error produces large errors at most image points. Because the halftone patterns vary rapidly these differences are blurred by the eye, and the reproduction may still preserve the appearance of the original.

In this paper, we present an extension of the CIELAB color metric that can be applied to measuring color reproduction errors in images. We refer to the extension as Spatial-CIELAB (S-CIELAB).

3 Overview

We have two goals in designing the S-CIELAB error measure. First, we would like to apply a spatial filtering operation to

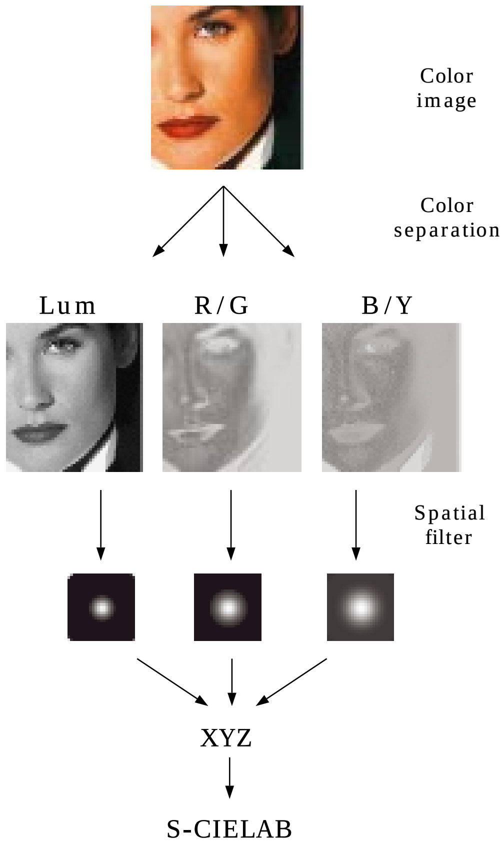

Figure 1: A flow-chart showing how to compute S-CIELAB.

the color image data in order to simulate the spatial blurring by the human visual system. Second, when the inputs are large uniform areas, we would like the extension to be consistent with the basic CIELAB calculation.

Figure 1 shows how to calculate the S-CIELAB representation. The image data are transformed into an opponent-colors space. Each opponent-colors image is convolved with a kernel whose shape is determined by the visual spatial sensitivity to that color dimension; the area under each of these kernels integrates to one. The calculation is pattern-color separable because the color transformation does not depend on the image's spatial pattern, and the spatial convolution does not depend on the image's color.

Finally, the filtered representation is transformed to a CIE-XYZ representation, and this representation is transformed using the CIELAB formulae. The resulting S-CIELAB representation includes both the spatial filtering and the CIELAB processing.

We use a pattern-color separable transformation for two reasons. First, separable transformations are efficient to compute. Second, psychophysical experiments suggest that the human visual representation of simple colored patterns is pattern-color separable (Poirson & Wandell, 1993, 1996; Bäuml and Wandell, in press). The parameters in the S-CIELAB calculation, including the color transformation and the spatial filters, were estimated from these psychophysical measurements.

Differences between the S-CIELAB representation of an original image and its reproduction measure the reproduction error. We summarize these differences by a quantity ΔE_s, which is computed precisely as ΔE in conventional CIELAB. The S-CIELAB difference measure reflects both spatial and color sensitivity, and it equals the conventional CIELAB over uniform regions of the image.

4 Implementation

To specify the S-CIELAB transformation, we must choose a color transformation and three spatial filters. In the calculations below, we used the transformation and filters estimated from human psychophysical measurements of color appearance. The color transformation converts the input image, specified in terms of the CIE 1931 XYZ tristimulus values, into three opponent-colors planes that represent luminance, red-green and blue-yellow image. The linear transformation from XYZ to opponent-colors is

$$\begin{aligned} O_1 &= 0.279X + 0.72Y - 0.107Z \\ O_2 &= -0.449X + 0.29Y - 0.077Z \\ O_3 &= 0.086X - 0.59Y + 0.501Z \end{aligned}$$

The data in each plane are filtered by two-dimensional separable spatial kernels of the form

$$f = k \sum_i w_i E_i$$

where

$$E_i = k_i \exp[-(x^2 + y^2)/\sigma_i^2].$$

In the discrete implementation, the scale factor k_i is chosen so that E_i sums to 1. The scale factor k is chosen so that for each color plane, its two-dimensional kernel f sums to one.

The parameters (w_i, σ_i) for the three color planes are:

Plane	Weights w_i	Spreads σ_i
Lum	0.921	0.0283
	0.105	0.133
	-0.108	4.336
Red-green	0.531	0.0392
	0.330	0.494
Blue-yellow	0.488	0.0536
	0.371	0.386

where spread is in degrees of visual angle.

Because the spatial processing stage is separate from the CIELAB calculation, we can implement S-CIELAB as a pre-processor to existing CIELAB-related software or hardware. The separability of the pattern and color stages makes it straightforward to apply the spatial extension to other color difference calculations.

5 Results

We tested S-CIELAB on JPEG-DCT compressed images, halftoned images, and some simple test patterns (e.g., sweep frequency color images). Some of these methods, such as the JPEG-DCT and halftoning, are designed to take advantage of the spatial insensitivity of the eye to certain colored patterns. Figure 2 shows how the JPEG-DCT transforms three opponent-colors planes of an image. This image was created using the standard JPEG-DCT compression algorithm with a quality factor set to 75, so that the compressed image appears only slightly different from the original. At this compression level, the luminance plane is blurred slightly (A), while the red-green and blue-yellow planes are blurred strongly (B,C). The chromatic blurring is barely visible in the compressed image, much as the loss of spatial resolution in the chromatic channels of the NTSC signal is barely visible in the television picture (Wandell, 1995, p. 326 et seq.).

The CIELAB and S-CIELAB reproduction errors for the compressed image are compared in Figure 3. The solid line shows the distribution of ΔE values computed point-by-point using CIELAB on the original and compressed image. The CIELAB error distribution of ΔE values had 36 percent of the image exceeding 5 units, and 10 percent exceeding 10 units. When comparing the color reproduction of large uniform fields color differences of this size are easily visible; in the reproduction, however very few errors are visible. Hence, these ΔE values are larger than the perceived difference. The dashed line shows the distribution of ΔE_s errors between the original image and the JPEG-DCT compressed image. In this case only 5 percent of the image exceeded 5 units and 0.2 percent exceeded 10 units. These numbers are consistent with the visual similarity between the two images.

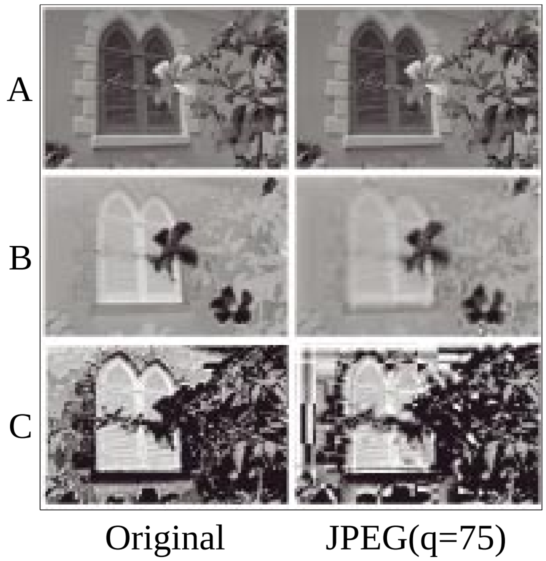

Figure 2: The effects of JPEG-DCT compression on the (A) luminance, (B) red-green, and (C) blue-yellow planes. The quality factor was set to 75. The blurring and block artifacts are very strong in the blue-yellow plane.

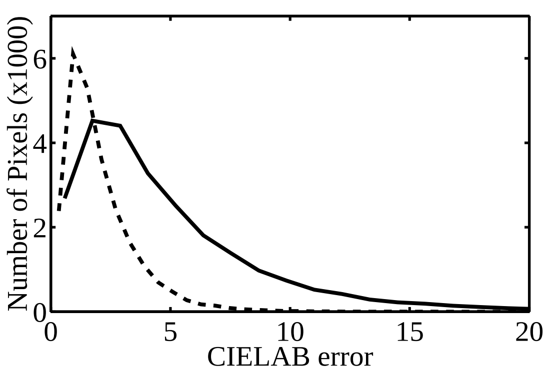

Figure 3: Distributions of the CIELAB ΔE (solid line) and S-CIELAB ΔE_s (dashed line) reproduction errors between the original and compressed flower image, assuming an 18 in viewing distance. Viewed at this distance on a 90 dpi monitor the images appear very similar.

Because CIELAB was not designed with digital image applications in mind, it should not be applied to evaluate the reproduction error for JPEG-DCT images (or halftones). By adding a spatial pre-processing stage, S-CIELAB extends CIELAB to reproduction errors of digital images.

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