Prediction of the texture visibility of color halftone patterns

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Abstract. *We propose a metric to predict the visibility of color halftone textures. This metric is represented by the critical viewing distance below which the halftone textures can be discriminated. It is intended to be used in the evaluation of the texture visibility of uniform color halftone peaoerns, which plays an important role in halftone design and optimization. The metric utilizes the visual threshold versus intensity function and contrast sensitivity functions for luminance and chrominance. To verify the metric, the texture visibility was deoermined experimentally using a psychovisual experiment. The critical viewing distances deoermined by the experiment and those predicted by the metric were compared, and a good correlation was achieved. The results have shown that the metric is capable of predicting the visibility over a wide range of texture characteristics.* [DOI: 10.1117/1.1455010]

1 Introduction

Halftoning design and optimization largely relies on the quantitative measurement of the quality of halftone patterns. For example, the blue noise mask (BNM)[1,2] algorithm requires a criterion by which to co.tochecptimizat viewing distance or displaying resolution so that the halftone textures of a uniform color pattern appear to be just noticeable, or whether or not a uniform color halftone pattern is visible to the human eye under a given viewing condition. Designed as a quality metric at the threshold level, this metric is useful for halftone design in which a stopping criterion is often required for optimization of each gray level, as well as evaluation of the quality and for a comparison among different halftone techniques.

In Sec. 1.1, the definition of the FWMSE is given and its limitations are illustrated. In Sec. 1.2, the idea that led to the development of this metric is presented.

1.1 *FWMSE*

FWMSE is the widely used quality metric in many imaging applications. How to calculate the FWMSE is illustrated in Fig. 1. In halftoning, the frequency weighted errors between a continuous image and its halftoned version are evaluated. The frequency factors used in the evaluation are the frequency responses of the human visual system. Thus, larger weighting factors are used for the frequencies to

$$H_c(f_r) = \begin{cases} 1.98(0.192 + 0.342 f_r)\exp[-(0.342 f_r)^{1.1}], \\ \quad \text{if} \;\; f_r > f_{\max}, \\ 0.9 \quad \text{otherwise}, \end{cases} \tag{8}$$

where f_r in Eqs. (7) and (8) denotes the radial spatial frequency in units of cycle/deg, and $f_{\max}$ in Eq. (8) is the frequency in which $H_c(f_r)$ reaches its maximal value.

1. Start with the displayed image represented in the device's RGB space.
2. Convert the representation in the device's RGB space to the device's independent XYZ space.
   The conversion was implemented by the matrix operation

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = T \times \Bigg(\text{R}$$

$$\mathrm{STD}=\mathrm{std}(y')+\mathrm{std}(o_1')+\mathrm{std}(o_2'), \quad (18)$$

where STD is the observed error in the image.

5 Experiment

We now introduce an experiment to determine the visibility of halftone patterns subjectively. As explained in Sec. 1, we will examine the critical viewing conditions that cause marginal perception experimentally. Since continuously adjusting the display resolution is impractical, we used a fixed resolution to present the stimuli and changed the viewing distances instead.

5.1 *Apparatus*

A 21 in. SGI monitor was used to display the stimuli. The monitor was characterized by a tristimulus colorimeter. The luminance of the white point is 55.2 cd/m^2. The tristimulus values (X, Y, Z) of the RGB phosphors were measured. The matrix T to convert from the device's RGB space to the XYZ space was obtained from the following characterization:

$$T=\begin{pmatrix} 0.4070 & 0.3042 & 0.2269 \\ 0.2256 & 0.6927 & 0.0817 \\ 0.0270 & 0.1424 & 1.2043 \end{pmatrix}. \quad (19)$$

Since all the target patterns in this experiment are halftone patterns, the phosphors were at a status of either "on" or "off," so no gamma correction is needed. The advantage of using displayed images as stimuli is that it is easy to program and control the display sequences.

5.2 *Stimuli*

All the stimuli used in this experiment were color halftone patches. To reduce the effect of the modulation transfer function (MTF) of the monitor, each pixel was duplicated twice in both the horizontal and vertical directions, and the effective display resolution was 43 dpi. The images were 512×512 pixels, and all the stimuli were 15 cm×15 cm squares. The stimuli were displayed in the center of a uniform medium gray background. During the experiment, only one stimulus was presented on the screen each time. The experiment was conducted under conventional office lighting with fluorescent illumination and without sunlight or visible glare on the display8 the 068 0 605stheo.pBcoinoc9.7rl(display)(the-)]TJ -1.2 -1.J T* [59.9he expventi59.9h-457.6(stim6es)-404.tim6 termine the best position. The distances at which they were able to just detect the texture of the halftone patterns were recorded.

The whole experiment was divided into four sessions to prevent observer fatigue. In each session one set of color images was used as the stimuli. The four sessions were assigned at different but successive time segments. Each subject took only one session in one time segment. The patterns were presented twice in random order. For each pattern, the difference between the two measurements was calculated promptly. If the error was larger than a predetermined value, the pattern would be displayed one more time in the same session.

5.4 *Results*

Six subjects participated in the experiment. The mean values of all the observers are listed in Table 1. A graphic representation of the results will be given in Figs. 7 and 8 in Sec. 6, where a comparison with the metric defined in Sec. 4 is illustrated. Generally, the error diffusion patterns resulted in overall smallest distances. This means that the error diffusion patterns had the least amount of visibility among all the types of patterns. The dot-off-dot (mutually exclusive masks) outperformed the dot-on-dot patterns, especially for the gray patches. For the Bayer's patterns at optimal levels, for example, at 25%, 50%, and 75%, the visibility was very low. However, for other levels of Bayer's patterns, the visibility was very high, particularly for some color patterns.

6 Discussion

6.1 *Correlation Between the Metric and Experimental Results*

A threshold factor of 1/40 was used as factor c in Eq. (16). This fraction is in the range of a typical factor for perception by eye.[20,32] From the calculations and a comparison with the experimental data, a factor of 1/40 was found to be the most suitable to define the visual threshold factor. In this paper, the intensities were scaled according to the reference white point on the monitor, which was normalized to 1. The threshold is a fraction of the square root of the intensity, so the factor should be multiplied by a scale factor if another intensity unit is used or if the dynamic range work.[25–27] Also, the two factors were adjusted within a small range during metric development, and they had no large effect on the results of the metric predicted so the CSF again is found to provide a useful description of the achromatic and chromatic characteristics of the visual system in this case.

It can be seen that a strong similarity exists between the procedure for the experiment and the algorithm to derive the critical viewing distance. The algorithm can be considered as simulating the process of walking back and forth and adjusting to the position at which the observer can barely discriminate the texture. Changing the viewing distance causes a shift of the HVS model in the discrete frequency domain, and thus causes a change in frequency content that could be captured by the eye. As the observer walks closer to the monitor, the spatial variation of the pattern increases, and the critical distance is that where the total error just exceeds the visual threshold.

The experimental results and the distances calculated by the proposed metric are illustrated in Figs. 7 and 8. The x axes in Figs. 7 and 8 are the distances predicted by the metric, and the y axes are the experimental results. Figure 7 illustrates the mean values for all the observers versus the predicted values. Figure 8 is the same as Fig. 7 except that standard deviations are included. By inspecting Figs. 7 and 8, it can be seen that a good linear correlation exists between the experimental results and the metrics. The linear correlation coefficient of the data is $r=0.88$.

The standard deviation of the images was used as the average of the increment in intensity versus the uniform background. Kaiser and Boynton have discussed the issue of interaction between opponent color channels[33] and they specified the empirical rule for the interaction as:

$$F=[|r-g|^n+|y-b|^n]$$

terns. The intensity levels tested in this experiment were