Exploring Free-Energy Principle for Spatial Masking Estimation in Color Images

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***Abstract*—The Human Visual System (HVS) has a limited sensitivity in perceiving visual information such that visual masking estimation is helpful to improve the performance of image processing techniques. Most existing research efforts only focus on the methods of assessing the visual masking for gray images. In this paper, a spatial masking estimation utilizing the free-energy principle is explored for color images. According to the free-energy principle introduced recently, the HVS is sensitive to the orderly stimulus possessing structural regularity which is easily to be predicted and is insensitive to the disorderly stimulus containing structural irregularity. We reasonably deduce that the spatial masking in color images may be overestimated in the region with orderly structures and underestimated in the region with disorderly structures. Based on a simple prediction model imitating the brain works of the HVS, the structural irregularity is computed to formulate a more accurate spatial masking function of color images. The masking function is further extended to build a color visual model of estimating the visibility thresholds of color images for performance comparison. Simulation results demonstrate that the proposed spatial masking estimation for color images has better consistency with the HVS than the existing method.**

***Index Terms*—HVS, spatial masking, free-energy, structural irregularity**

I. Introduction

For the growing amount of digital images transmitted over the internet, it becomes important for designing image processing techniques to consider the characteristics of the mechanism in the Human Visual System (HVS) directly. The well-known properties that the HVS has a limited sensitivity in perceiving visual information are always utilized to represent images more efficiently. Through assessing the human visual sensitivity inherent in images, the performance of many techniques of saliency detection [1], quality assessment [2], [3], image compression [4]-[6], and watermarking [7]-[9] *et al.* has been improved in the perceptual research community. Quantitatively, the human visual sensitivity can be measured by the visual masking estimation. All of these researches, however, concentrated only on the estimation and exploitation of the human visual masking inherent in gray-scale images.

The human visual masking inherent in color images results in that the HVS does not respond to small stimuli and is not able to discriminate color signals of small differences. The perceptual image processing application for color images can be found in [6], [9], [10]-[12], some of which [6], [10]-[12] take the characteristics of the human visual perception of color stimuli into account. By using different levels of Just Noticeable Color Difference (JNCD), a simplified visual model introduced in [6] for estimating the perceptual redundancy for each color pixel as the visibility threshold of color difference was proposed to modify the coding efficiency of two existing image coders. In [10], a metric for assessing the quality of color images was proposed. The metric measures the average perceptible distortion in terms of the quantized distortion, according to the perceptual error map converting the color difference to the objective score of perceptual quality assessment. Zhu and Karam [11] proposed a perceptual based no-reference objective image quality metric by integrating perceptually weighted local noise into a probability summation model. Unlike existing objective metrics, the proposed no-reference metric is able to predict the relative amount of noise perceived in images with different content, without a reference. In [12], a copyright identification scheme for color images that takes advantage of the complementary nature of watermarking and fingerprinting was proposed to embed the watermark into the less sensitive R and B channels of the host image in the RGB color space. To gain high performance in color image processing, the properties of the human visual perception of color stimuli must be well utilized in exploring the spatial masking estimation of color images.

The newest research efforts declare that effective analysis of the image structures can be used to deduce accurate estimation of visual masking. The concept of the free-energy principle indicates the brain works actively predict the input scenes and avoids the residual uncertainty/structural irregularity [13], [14]. In this paper, the free-energy principle is utilized to estimate spatial masking for color images. Based on a simple prediction model, the luminance dominated structural irregularity is taken into account to explore a more strict spatial masking function in color images, while only background non-uniformity and texture content are used in the prior works. To avoid underestimating or overestimating the spatial masking effect in the region with structural uncertainty, the nonlinear additivity model is adopted to

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build a new masking function. By using this function, the visibility thresholds of color images are estimated for performance comparison under a fair viewing test.

The remainder of this paper is organized as follows. Section II describes the proposed spatial masking based on the structure information. In Section III, we evaluate the performance of the improved spatial masking by comparing the accuracy of estimating the visibility thresholds of color images. The simulation results are given in Section IV and the final section concludes the paper.

II. Improved Spatial Masking Estimation Based on Structure Information

In this section, the analysis of structural irregularity for image perception is extended to color images for spatial masking estimation. According to the free-energy principle recently introduced in [14], the input scene information received by human eyes is not fully processed by the HVS and some information with structural irregularities is avoided and hard to be predicted. The HVS is highly adaptive to extract orderly structures and tries to avoid disorderly structures or structural irregularity [15]. That is, the human visual perception of brain works understands the orderly stimulus which is easily to be predicted and ignores the structural irregularity which is hard to be precisely predicted. To accurately measure the perceptual redundancy of color images, the structure information is utilized to improve the spatial masking estimation in the color image.

In [6], the spatial masking effect considering the local color image context is exploited to calculate variable Just Noticeable Color Difference (JNCD) or variable JNCD (VJNCD) of each color pixel in the uniform CIELAB color space. By using the colors on the surface of the VJNCD sphere, the perceptual redundancy inherent in each color pixel in color images can be estimated. In this section, the structural irregularity is incorporated to improve the prior texture masking function, $s_L(E(L_x), \Delta L_x)$, for pixel x of the color image in the CIELAB color space, where the function is primarily induced by average background luminance $E(L_x)$ and luminance gradient ΔL_x of the pixel. The new spatial masking function is defined and given by

$$M(x) = f(\, s_L(E(L_x), \Delta L_x), s_U(LR_x)\,) \quad (1)$$

where $s_U(LR_x)$ is the corresponding structure-based adjustment caused by considering the amount of luminance residual LR_x, and f a function used to control the overlapping between $s_L(E(L_x), \Delta L_x)$ and $s_U(LR_x)$. For simplicity, only the luminance dominated structural irregularity inherent in the color image is investigated, while considering the fact that the human eye is more sensitive to luminance than to chrominance.

As mentioned above, the structural irregularity of an image is from the uncertain information which is hard to be predicted for the HVS. We reasonably regard the uncertain information of the image as the residual part between the image and its prediction part [16]. An computational prediction autoregressive (AR) model for the luminance component of the color image is therefore exploited and given by

$$L'_x = \sum_{x_i \in \Re} p_i L_{x_i} + \nu_x \quad (2)$$

where L'_x is the predicted luminance value of pixel x, x_i the i-th neighboring pixel in the surrounding region $\Re = \{x_1, x_2, \dots, x_N\}$ and k=1 to N (such as N=8 for a 3×3 surrounding square region), and $\{p_i\}$ the model coefficients which are determined by minimizing the variance of the white noise $\{\nu_x\}$. The residual part is then computed as follows:

$$LR_x = |L_x - L'_x| \quad (3)$$

Based on the free-energy principle, the HVS tries to avoid structural irregularity while receiving the input scene. That is, the signal in the irregular region can mask or conceal more noise without noticing by the human visual perception. Therefore, a pixel in the image with large residual value means the pixel is difficult to be predicted and has high uncertainty with large structural irregularity. The relation between the structure-based adjustment and the residual part of the pixel in the image is obtained by fitting the empirical data under the subject viewing tests and the experimental results.

(a) (b)

Figure 1. (a) Original color image of "Pepper" and (b) its noise contaminated image (PSNR=33.20dB)

III. PERFORMANCE VERIFICATION OF THE IMPROVED SPATIAL MASKING

The performance of the proposed structure-based spatial masking adjustment is verified by incorporating (1) into Chou's model [6] to compare the accuracy of estimating the visibility thresholds of color images. For a particular color pixel, the perceptual redundancy is quantitatively measured by analyzing the loci of colors which are perceptually indistinguishable from this color. In [6], the loci form a sphere centralized at this color's coordinate with the radius of VJNCD in the uniform CIELAB color space and used to compute the visibility thresholds of color pixels in color images. In this paper, the VJNCD of the color pixel x within a complex image is redefined by replacing $s_L(E(L_x), \Delta L_x)$ with (1).

The procedure for estimating the perceptual redundancy of a pixel in an arbitrary color space is firstly to transform the color pixel to the CIELAB space. By utilizing the improved spatial masking function presented in this paper, the corresponding improved VJNCD threshold is obtained according to the uniformity in the CIELAB space [17]. Under the perceptually conservative restriction controlled by the luminance, some critical colors on the surface of the VJNCD sphere are selected to transform back to the target color space. Finally, an approximate rectangular subspace is obtained to quantify the perceptual redundancy and the visibility thresholds of the color pixel for each color channel are calculated.

The performance of the improved spatial masking for color images is justified by comparing the accuracy of estimating the visibility thresholds of color images in each color component. Herein, a subjective test is conducted to inspect if the estimated visibility thresholds is consistent with the HVS. Suppose a test image is represented in the YC_bC_r color space, the visibility threshold for each color pixel in each color component of the color image is randomly added to or subtracted from the corresponding color pixel. While the visual quality of the contaminated image has nearly the same as the original image under the specified viewing condition, the accuracy degree of estimating the visibility thresholds is better if the PSNR of the contaminated image is lower.

IV. SIMULATION RESULTS

In the simulation, the spatial masking estimation is carried out for a variety of color images of size 512×512. The color pixels are represented in 24-bit YC_bC_r format. 16 subjects who have normal eyesight or had been corrected to be normal take part in test. In the viewing test, the original color image and its noise contaminated image are randomly placed side by side on the monitor (ViewSonic VX2363). The test is carried out in the dark room when the subject observes the image pair on the monitor at a viewing distance of six times the image's height.

In Fig. 1, the original color image of "Pepper" (Fig. 1a) and its noise contaminated version (Fig. 1b) of PSNR=33.20dB by the associated visibility thresholds in three color components are shown, while the two images are perceptually indistinguishable from each other under the viewing condition mentioned above. The PSNR comparison of the noise contaminated color images are shown in Table I, from which the improved spatial masking estimation based on the free energy principle indeed achieve larger noise concealment in the regions with structural irregularity, while the visual quality of the contaminated image has nearly the same as the original image under the specified viewing condition. The proposed spatial masking adjustment successfully shows better performance than the masking estimation presented in [6].

TABLE I. PSNR COMPARISON OF THE NOISE CONTAMINATED COLOR IMAGES

Channels	Chou's model [6]	Proposed method
Tulips	37.17dB	35.27dB
Zuerst	36.87dB	34.95dB
Goldhill	34.92dB	33.81dB
Pepper	34.75dB	33.20dB

V. CONCLUSIONS

In this paper, the improved spatial masking estimation based on the free-energy principle is presented for color images. By using the brain works of the human visual perception which is sensitive to the orderly stimulus that is easily predicted and is insensitive to the disorderly stimulus, the structural irregularity is estimated by incorporating a simple prediction model to effectively obtain a new spatial masking function. We use the function to compute the visibility thresholds of color images for performance comparison. With the new spatial masking function, the proposed spatial masking adjustment successfully shows better performance than the existing masking estimation.

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