Exploring the Effect of Color Distortion on the Quality of Subjective Visual Perception

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Abstract: Vision is the main channel for receiving information and the most important way to understand the objective world. As an important visual factor, color has a tremendous impact and plays an irreplaceable role in human lives. However, color perception is highly subjective and closely related to observational physiology and the psychological basis of the human eyes. The results of color perception can facilitate the complete understanding of image information. In this paper, we are dedicated to exploring the effect of color distortion on the quality of subjective visual perception via a series of large subjective video quality experiments. First, a large number of subjective quality assessments based on color damage were designed and performed, in which 11424 individual human quality judgments were obtained and used to analyze the visual perception of color distortion. Through a statistical analysis of the subjective experimental results, the effect of color distortion on visual perception was assumed from the perspectives of hue and saturation. Then, verification models were designed to ensure the accuracy and rationality of assessing the perceptual characteristics of color distortion. Finally, some conclusions about the effect of color distortion on the quality of subjective visual perception were obtained. The results show that in terms of hue, human eyes are sensitive to red, and the damage in red areas is most easily perceived. In terms of saturation, the human eye is sensitive to high saturation, and the damage in high-saturation areas is most easily perceived.

Keywords: Color; Distortion; Visual Perception; Subjective Evaluation

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1 Introduction

Vision is the main channel for humans to recognize and accept information, and it is the most important way to cognitively assess the objective world. As an important visual feature, color is related to the objects or scenes contained in an image. When the image is geometrically characterized via changes in size or shape, rotation or translation, the color remains stable. Color is also a main perceptual feature of image recognition [1]. Studies of color damage perception can facilitate the human understanding of the information contained in images.

Edwin Land [2] described the theoretical need for three independent color channels to explain human color constancy [3]. Schade suggested that the color contrast threshold is proportional to the square root of the luminance [4], and this definition was further expanded by Van der Horst and Bouma [5], Kelly [6], and Granger and Heurtley [7], who applied threshold methods in psychology and physics. Kelly and Mullen used the luminance contrast to represent the color change of spatial strips and further studied the color contrast sensitivity [8]. Combined with the visual perception characteristics of luminance, the color perception of the human eyes can be considered a low-pass filter. The characteristics of color vision mainly describe the subjective color perception response of human eyes, which needs to be based on a large number of subjective visual assessments. However, little subjective quality assessment research has focused on color damage perception. De Simonea [9] found that the subjective

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perception quality of color images is lower than that of grey images, further verifying the importance of color in image quality assessment. However, the experiment only validated the importance of color, and the number of human subjects was insufficient. Color is closely related to visual physiology and psychology. Since color perception is strongly subjective, researchers have not further studied the visual perception characteristics of color damage or conducted related experiments.

This work aims to provide the first contribution to color damage assessment. The novel study was conducted for multiple reasons. First, color perception provides a theoretical basis for further exploring image quality assessment technology based on visual perception, and it can enrich and improve color evaluation systems. Second, from the perspective of color, understanding color damage can promote the development of a more advanced image compression coding algorithm based on visual perception. Third, vision has become an important research direction for artificial intelligence. Studies of visual color perception can improve our understanding of color information processing in the brain and promote the exploration of human consciousness and thinking, thereby improving simulations and extending human intelligence.

This work presents the results of an extensive subjective quality assessment study in which the visual perception of color damage is investigated. First, a large number of subjective quality assessments based on color damage are designed and performed. Through a statistical analysis of the subjective experimental results, the visual perception of color damage is assumed from the perspectives of hue and saturation. Then, we design computational models to verify the scientific validity and rationality of the results. Finally, the visual perception of image color damage is obtained.

This paper is organized as follows. Section 2 gives the details of the subjective assessments of color perception. Section 3 presents the results, which are discussed and validated in Sec. 3.2. We conclude the paper in Sec. 4.

2 Details of the Experiment

Subjective quality assessment is performed to evaluate the quality of sequences according to observations, which can reliably and accurately reflect the subjective perception.

2.1 Test Material

The choice of the input material used in the psychovisual experiment is clearly related to the design of the methodology, and it is a critical factor that affects the significance of the collected subjective data. As an initial step, we restricted the field of investigation by considering a data set of videos that included references and distortions introduced by the H.264 and MPEG compression algorithm. Based on the material selection of the ITU-R BT.1788 subjective quality evaluation recommendation [10], and because there is no database for studying color damage, it is necessary to record the experimental materials according to their color characteristics. The experimental materials contain a variety of vivid colors, and each color occupies most of the screen. The materials have rich texture details to ensure that damage is noticeable. The chromaticity of the materials is within the standard hue range. Figure 1 shows a subset of the source materials used in the study. The chromaticity detection results are shown in Table 1.

Figure 1 Some source materials used in the study

Table 1 Chromaticity detection results from the Spectrascan photo research PR655 optical spectrum

Hue	**x**	**y**
Yellow	0.5142	0.4540
Cyan	0.1703	0.1545
Green	0.2616	0.6637
Magenta	0.3387	0.1838
Red	0.5788	0.2996
Blue	0.1536	0.0536

2.2 Test Environment

The experiments were conducted using identical Microsoft Windows workstations. The highly professional laboratory setup was designed in full agreement with the relevant recommendations issued by the ITU-R for the subjective evaluation of fixed and moving images. The laboratory setup was constructed in a manner that ensured the reproducibility of the subjective test activity by avoiding the involuntary influences of controllable external factors. The ratio of background brightness to peak brightness used for the high-resolution display monitor was 0.15. The indoor ambient light illumination was maintained at no more than 20 lux.

2.3 Human Subjects and Hypothesis Testing

An assessment by a group of experts is considered highly reliable and able to provide results validly [11]. The bulk of the subjects who took part in the study were recruited from the Radio and Television Engineering (undergraduate) and the Digital Image and Video Processing (graduate) classes at the Communication University of China.

Experts agree that the duration of the entire session, including training, should not exceed 45 minutes to minimize the effects of fatigue in the measurements. This threshold poses an upper limit on how many images can be evaluated in one session. To ensure the scientific validity of the experiment and avoid an unnecessary increase in the sample size, a hypothesis test was performed. The hypothesis test indicates whether the results of the subjective assessment, based on the number of sample points, can be used to make a statistically sound conclusion regarding the visual perception of color damage. Using the t-test and taking alpha as 0.05, it was determined that 19 subjects per session ensured that the statistical test power reached 0.86.

2.4 Test Methodology

In the case in which a vivid hue occupied most of the screen, due to the differences in brightness among hues, the brightness of yellow, cyan, green, magenta, red, and blue decreased in turn. Two sessions were established to explore the perceptual characteristics of hue by controlling the ambient illuminance and the visual subjective brightness.

The experimental setup used was based on a double-stimulus continuous quality scale methodology (DSCQS) [12, 13], which required subjects to evaluate video pairs consisting of an original reference video and a distorted video. The test material was presented in a pseudo-random order so that test pairs related to different original content always alternated. Specifically, the experiments were conducted in three sessions: hue perception research at certain ambient illumination levels, hue perception research at certain visual brightness levels and saturation perception research. The number of videos in each session is shown in Table 2.

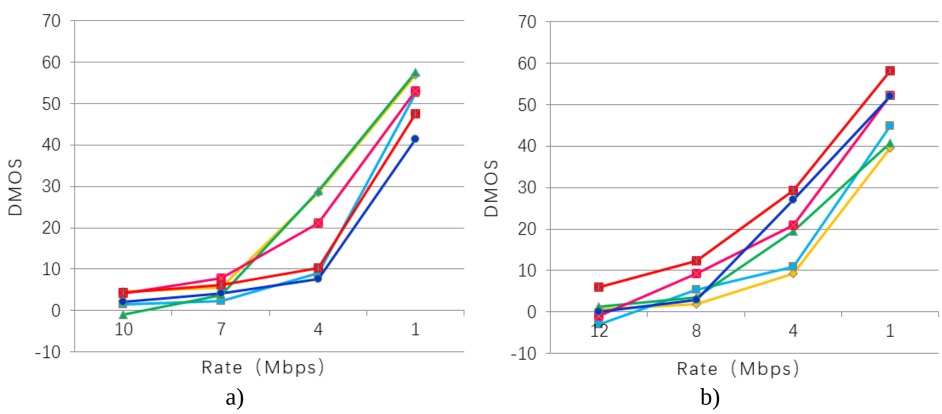


Figure 2 Subjective quality assessment results of hue damage perception: (a) under certain ambient illumination conditions and (b) under certain visual brightness conditions

Table 2 Subjective evaluation sessions: The number of images in each session and the number of subjects participating in each session

Session	Number of sequences	Number of individual quality judgements
Hue - at certain ambient illumination levels	114	3486
Hue - at certain visual brightness levels	120	3690
Saturation	144	4248
Total	378	11424

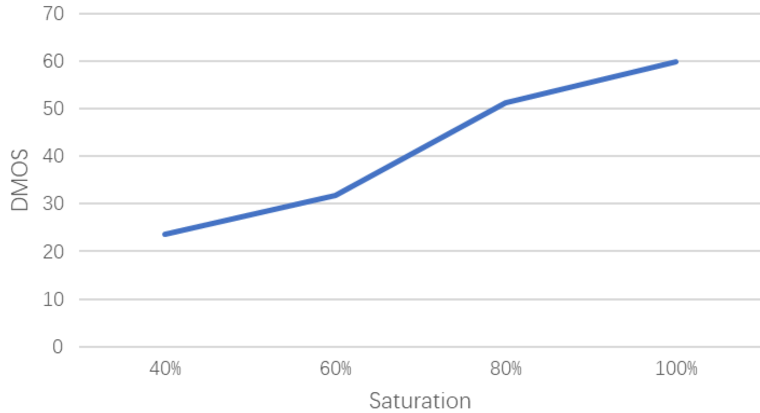


Figure 3 Subjective quality assessment results of saturation damage perception

3. Experimental Results

In terms of hue, yellow and green have relatively high differential mean opinion scores (DMOS) when the ambient illumination is constant; Red have relatively high DMOS when the subjective brightness is constant. That is, under certain ambient illumination conditions, the damage to yellow and green areas is more easily perceived. Additionally, under certain levels of visually perceived brightness, the damage in red areas is most likely to be detected.

In terms of saturation, DMOS tends to increase with increasing saturation. That is, the human eye is more sensitive to damage in high-saturation areas.

4 Discussion

4.1 Visual Color Damage Perception

In terms of hue, visual sensitivity to damage varies for different hues, and the brightness of the hue affects the sensitivity of the human eye to the damage in the given hue. Specifically, under certain ambient illumination conditions, the human eye is relatively sensitive to damage in the yellow and green areas since they are at high luminance levels, and the sensitivity to red area damage is moderate. If the visual perception brightness of each color is the same, the human eye is most sensitive to damage in red areas. In reality, the color of a subject being recorded is guaranteed to be in the appropriate brightness range. Therefore, it is more meaningful to describe the hue perception at same visual brightness levels, and human vision is more sensitive to red area damage.

In terms of saturation, within the color range, the visual resolution increases with increasing saturation, and the perceptual damage sensitivity also increases. Thus, damage in high-saturation areas is more easily perceived by the human eyes than damage in low-saturation areas.

4.2 Verification Models

4.2.1 Hue Damage Perception Verification Model

Explore the effect of hue on the perceptual characteristics of color damage.

i) Convert the reference image and the distorted image into greyscale images, and calculate the peak signal-to-noise ratio between the two grey images as a reference value. The expression for the peak signal-to-noise ratio is

$$PSNR = 10 \times log_{10}\left[\frac{(2^n-1)^2}{MSE}\right], \quad (1)$$

where MSE is the mean square error between the reference image and the distorted image.

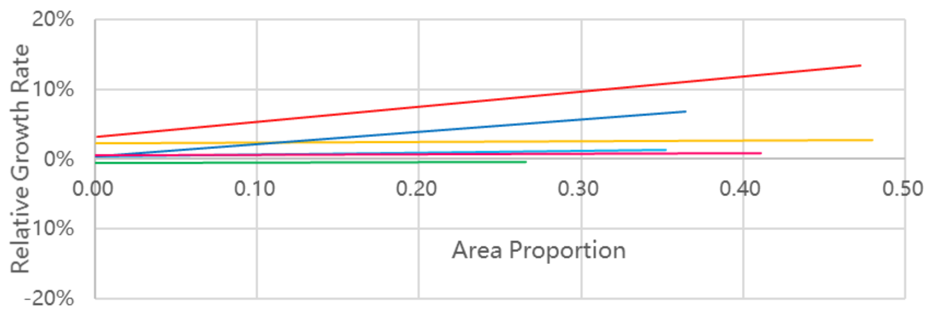
ii) Extract the large areas of yellow, cyan, green, magenta, red, and blue in the reference image, and expand the pixel value range in these regions of the distorted image. The peak signal-to-noise ratio between the processed image and the reference image is calculated.

iii) Calculate the correlation coefficient between the peak signal-to-noise ratio after processing and the mean opinion score, and compare this value with the correlation coefficient calculated based on the non-color values.

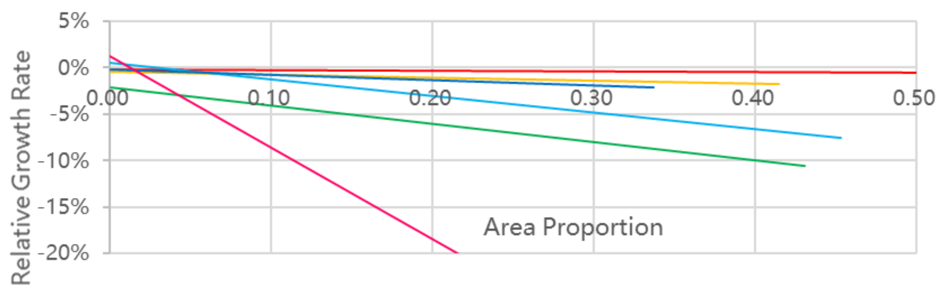
Because there is no image with uniform texture details for different hues in the existing database, each color region has different textures that affect the correlation coefficient comparison. Therefore, consider the relative growth rate between the Spearman rank-order correlation coefficient after processing and the correlation coefficient without color in order to eliminate the influence of texture on the results.

Taking red as an example, if red damage is more sensitive than other damage, when there is a certain area of red in an image, the damage in this area is more easily perceived, and the subjective scores should be lower than those of images with other hues. Extending the range of pixel values in the red region increases the MSE of the overall image, thereby reducing the peak signal-to-noise ratio and better matching the subjective scores. The peak signal-to-noise ratio after processing should display a higher correlation than that before processing, and the coefficient of red should notably increase. In contrast, if the human eye is not sensitive to damage in red regions, the peak signal-to-noise ratio calculated after extracting and extending the pixel value range of red regions will deviate from the subjective perception, and the correlation coefficient of red will not be superior to those for other colors.

Figure 4 shows the trend line of the relative growth rate for the correlation coefficients associated with yellow, cyan, green, magenta, red and blue hues considering the proportion of the color area. The processing of the red region can effectively improve the correlation between the peak signal-to-noise ratio and the subjective evaluation. The correlation coefficient increase for red is higher than that for other hues with the same proportional area.



a)



b)

Figure 4 The trend line of the relative increase in the Spearman rank-order correlation coefficient with the proportion of the color area: (a) TID2013 image database [14] and (b) LIVE image database [15]

4.2.2 Saturation Damage Perception Verification Model

Explore the effect of saturation on the perceptual characteristics of color damage.

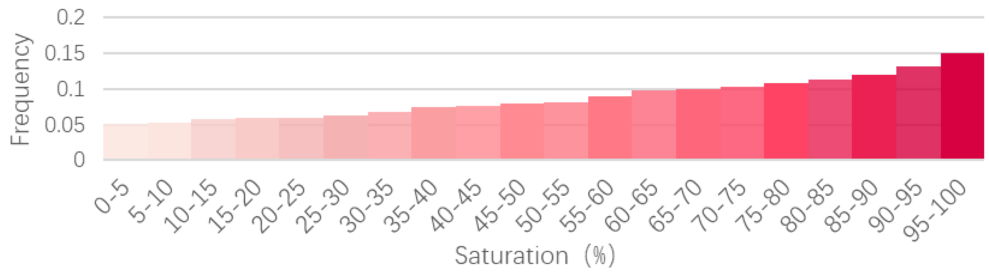
i) Calculate the color difference in corresponding pixels between the reference image and the distorted image according to Eq. (2) [16]. The color difference formula represents the perceptual difference between two points based on the tricolor coefficients. The computing results quantitatively reflect the color difference.

$$\Delta E^{*}_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}}, \quad (2)$$

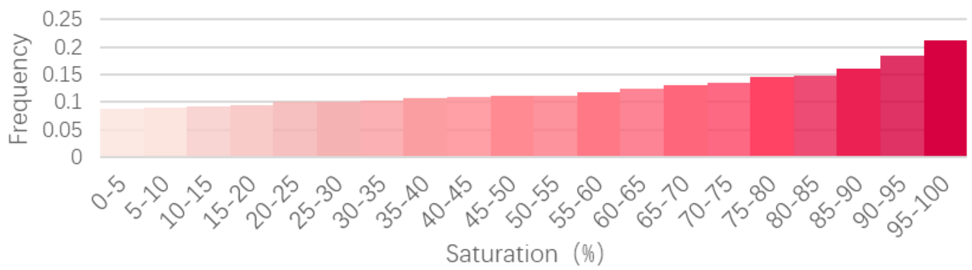
ii) Pixels with large CIEDE 2000 color difference values are extracted, that is, points sensitive to color damage are considered. The saturation values of these points in the reference image are calculated, and the number of color-sensitive points in each saturation interval is determined.

iii) Considering the effect of the image saturation distribution on the result, the number of sensitive points is divided by the total number of pixels of a given saturation level in the reference image.

To avoid contingency issues, the proportions of color-sensitive points under the two thresholds of CIEDE 2000 color differences (2.8 and 1.8) are calculated. The results show that the pixels with color difference values greater than 2.8 account for 0.06% of all pixels, and the pixels with values higher than 1.8 account for 28.27% of all pixels. Therefore, the color difference threshold selected in this verification model is 1.8. Figure 5 shows the distribution of points sensitive to color damage at various saturation levels. The frequency of the color-sensitive points increases with increasing saturation. The greater the saturation level is, the larger the proportion of sensitive pixels. This finding suggests that the damage in high-saturation regions is most easily perceived by the human eyes and that the sensitivity increases with increasing saturation.



a)



b)

Figure 5 Frequency distribution of color-sensitive points at various saturation levels: (a) TID2013 image database and (b) LIVE image database

5 Conclusion

This work has designed and performed subjective assessments to analyze the visual perception of color distortion. A model of exploring the effect of hue and a model of exploring the effect of saturation were designed to verify the rationality of the perceptions. Then, the visual perception of color damage was obtained. In terms of hue, the human eye is most sensitive to red, and the damage in red areas is most likely to be detected. In terms of saturation, the human eye is most sensitive to high-saturation colors, and the damage in high-saturation areas is most likely to be detected.

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