Multidimensional Structure of Colorfulness: Chroma Variation in Color Images of Natural Scenes

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Abstract

In a previous investigation it was found that the perceptual quality of images of natural scenes depended upon their subjective colorfulness when the images were transformed by varying of chroma.[1] The transformations were performed over the color point distributions in the CIELUV perceptually uniform color space where each color point represented one pixel of a corresponding image. The experiments with uni-dimensional scaling of colorfulness have shown that the colorfulness can be represented as a linear combination of average chroma and variability of chroma. However, such a representation held only within each scene: there was no regular rule to compare different scenes even with significantly different average chroma of the original images. The results of multidimensional scaling of colorfulness reveal the multidimensional structure of this attribute. Possible interpretations of subjective dimensions are discussed.

Introduction

The rapid advance of digital color imaging applications for professional use and entertainment, places increasing demands on image reproduction. These demands can only be met when psychological and perceptual factors are taken into account equally with technical issues. The obvious reason is that quality of displayed images is judged based on the perceptual attributes such as brightness, contrast, sharpness, colorfulness, etc.[1,2,3,4] These global attributes, in turn, are determined by many (physical) parameters, like blur, periodic structure, noise and others. Numerical category scaling experiment has shown that colorfulness of an image depended on an average chroma and a standard deviation of the chroma over the image when those parameters were varied for original images of four natural scenes.[1] However, the experimental data did not reveal the differences between scenes though the scenes had essentially different average chroma. Further investigation of global colorfulness and changes of this characteristic due to chroma variation of color images of natural scenes has been performed in a multidimensional scaling experiment. This study continues the series of investigations of image transformations and their perceptual relevance.

Method

Subjects

Six subjects participated in the experiment. They had normal or corrected-to-normal visual acuity and normal trichromatic color vision, checked with the H-R-R Pseudoisochromatic Plates.[5]

Stimuli

All images were prepared using a Gould deAnza Image Processing System IPS8400. Pictures of four natural scenes were used: a portrait of a female model (WANDA), an outdoor scene (TERRASGEEL), fruit displayed in front of a greengrocer's shop (FRUIT), and an abstract sculpture with bushes (STADHUIS). Slides of these scenes were scanned and digitized with 24 bits per pixel to obtain R, G, and B values. The images were described by their color point distributions in the CIELUV perceptually uniform color space. Every point corresponded to one pixel. Reference white was D_{65}. New images were generated by either multiplying the chroma value by a constant or adding a constant to the chroma value for every pixel of original images. If, during the processing of the images, calculated values were out of the possible range for the gray values of the monitor, the nearest possible value of chroma was used (clipping). The lightness and hue-angle were kept constant. The experimental set included 20 images: one original image plus two images obtained by multiplication and two images obtained by addition for every scene. For every image resulting average chroma and its variability (standard deviation of chroma) were computed. Additionally, the color point distributions in the CIELUV space were analyzed by the ISODATA clustering procedure.

Procedure

The images were displayed on a 70 Hz Barco CCID7351B monitor placed in a dark room. Images were presented for five seconds in sequential pairs. All pairs were randomly presented four times to every subject. During the two-second interval between image exposures and three-second interval between pairs of stimuli, a 4.6 cd/m^2 adaptation field appeared on the screen. The subjects had to judge the differences in colorfulness between images by integer numbers from zero (no differences in colorfulness) to nine (maximum differences in colorfulness). Colorfulness was defined as ‘presence and vividness of colors in the whole picture.’

Results and Discussion

The 20×20 triangle matrix of averaged over the subjects subjective differences between the images was treated by nonmetric multidimensional scaling algorithm. The dimensionality of the subjective space (Euclidean) of colorfulness was chosen equal to three. This was based on the formal criteria, like the values of stress and coefficients of correlation between subjective differences and Euclidean distances; order in location of images within the dimension and potential interpretability.

The coefficients of correlation of subjective differences and Euclidean distances for the one-, two- and three-dimensional solutions were 0.852, 0.919 and 0.951, respectively. The value of stress was 0.38 for the 1D solution, 0.15 for the 2D, and 0.06 for the 3D one. The higher dimensions were rejected because there was random location of the images along those axes that could not be comprehensively interpreted.

The arrangement of the images belonging to every scene along the first axis (Figure 1, a) corresponded to the results obtained in the experiment with the uni-dimensional scaling of colorfulness.[1]

The dependency of the magnitude of the first coordinate in the three-dimensional space of colorfulness on both average chroma and variability of chroma (standard deviation) can be efficiently described by a linear combination of these two variables, or:

X_1 = *A x Average chroma + B x Standard deviation of chroma + C,*

where the constants *A*, *B*, *C* do not depend on a scene, unlike in the case with the uni-dimensional scaling.

The coefficient of multiple linear regression amounted to 0.83. Both variables and a free constant were significant ($p<0.01$ for the average chroma; $p<0.05$ for the standard deviation of chroma, and $p<0.001$ for the constant). Figure 2 demonstrates the close accordance between X_1 coordinates and calculated values for all twenty images. The *A*, *B*, and *C* constants were equal to 0.015; 0.021 and 1.006, respectively.

The other two axes, however, reflect properties of the scenes per se. On the X_2X_3 plane (Figure 1,b) the images were located in the compact groups where each group included the pictures of one particular scene.

Along the X_2 axis the groups of images were arranged presumably according to the scene’s average lightness. The images “TERRASGEEL” had the greatest values of the X_2 coordinate and the highest average lightness - 46.31. They were followed by the images of “WANDA” (44.14), “STADHUIS” (43.47), and “FRUIT” (37.60).

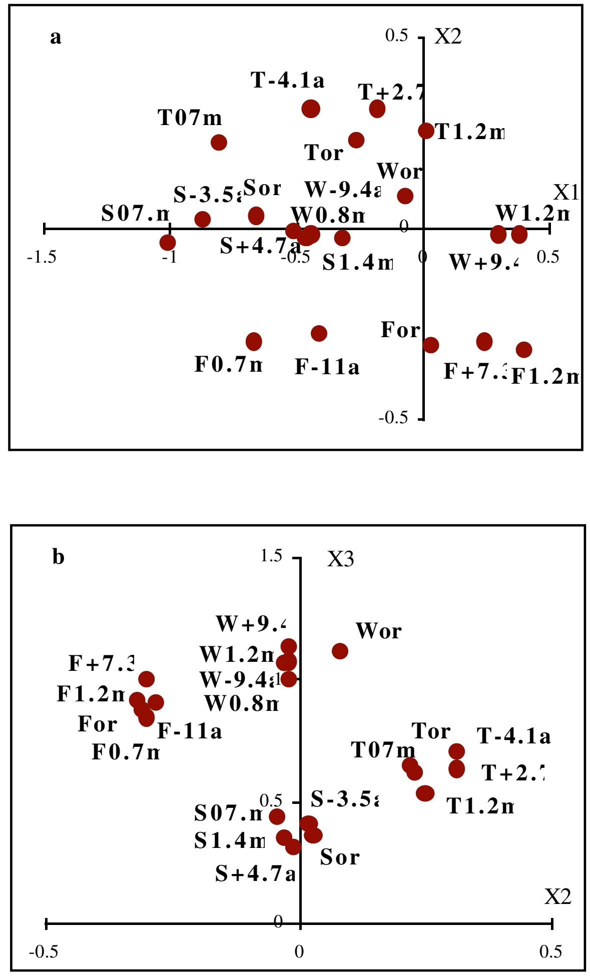

Figure 1. Projections of the images in the three-dimensional space of colorfulness on the X_1X_2 plane (a) and X_2X_3 plane (b). Upper-case letters W, F, T, and S designate the images belonging to the scenes “WANDA”, “FRUIT”, “TERRASGEEL”, and “STADHUIS”, respectively. Numbers indicate the constant used to vary the chroma value. Low-case ‘m’ stands for multiplication; ‘a’ for addition; ‘or’ means original image.

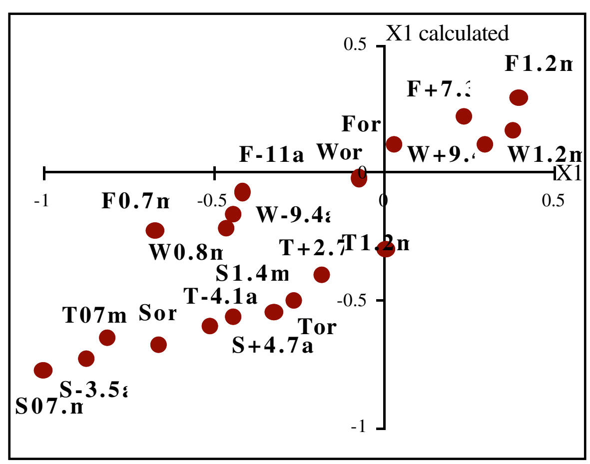

Figure 2. The experimental X1 coordinates of the images plotted versus values calculated as a linear combination of average chroma and its standard deviation (symbols: see Figure 1).

The coefficient of linear correlation between the X_2 coordinate and overall lightness was 0.95. Figure 3 demonstrates the linear correspondence between those variables.

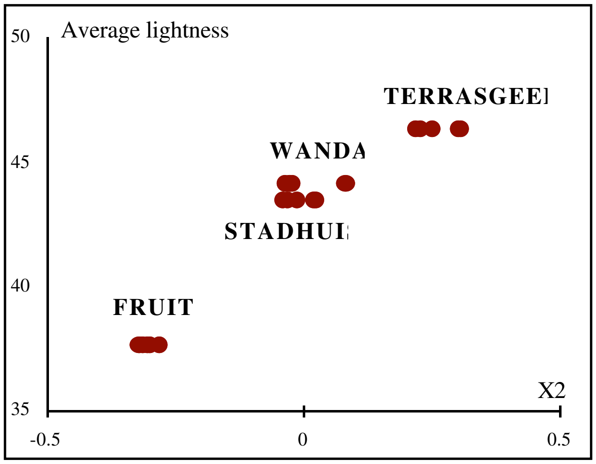

Figure 3. The experimental X2 coordinates of the images plotted versus their average lightness. The images are located in the compact groups according to the scenes.

This finding, concerning the contribution of the overall lightness into global impression of image colorfulness, has much in common with known from psychophysics data about interaction between saturation and brightness.[6]

For the third dimension there was no single interpretation although images were clearly grouped according to the scene. One can notice, however, that the sequence of the scenes along this scale reflects the order of the scene's average chroma. To elucidate more precisely the meaning of this factor more different scenes have to be used in the experiment.

Important information can also be derived from the individual data. It should be emphasized that the individual differences between subjects might be quite substantial reflecting both subjective experience as well as individual understanding of experimental instructions. As it has been supposed, subjects may use different strategies. Some of them, instead of comparing images by means of absolute-value scale, tended to use separate, relative-value scales for each of the four scenes[7].

The data of one subject demonstrates the dependence of the results on subjective experience. This subject participated in a considerable number of preliminary experiments including multidimensional scaling experiments. His subjective space of colorfulness was three-dimensional. The coefficient of correlation between Euclidean distances in this space and subjective differences amounted to 0.952. The first two axes were similar to the averaged data. Thus, the coefficient of the multiple linear regression that expresses the relation of the first dimension and average chroma and its variability was 0.90. For the second dimension, presumably associated with lightness, a coefficient of correlation was 0.91. The distribution of the images along the third dimension, however, differed from the averaged data. There were no distinct groups related to the scenes. A large experience of this subject in scaling and good results for the first two dimensions suggested that observed more uniform distribution of the images within the third axis was not accidental. This subject could use more precise criteria while estimating the differences in colorfulness that were masked by averaging. The third axis in this case has been interpreted as a color diversity in a picture. The color diversity we considered as reflecting how many different groups of colors are present in a picture. Intuitively, colorfulness is related to a number of different colors and their perceptual remoteness from each other. The more colors are in a picture, the more different or perceptually distant they are, the more colorful the picture appears. The quantitative index of color diversity for every image was calculated as a product of a number of clusters in the CIELUV color space, obtained using the ISODATA clustering algorithm and an averaged distance between those clusters. Calculated values highly correlated with X_3 coordinates of the images: the coefficient of linear correlation was equal to 0.81 (Figure 4).

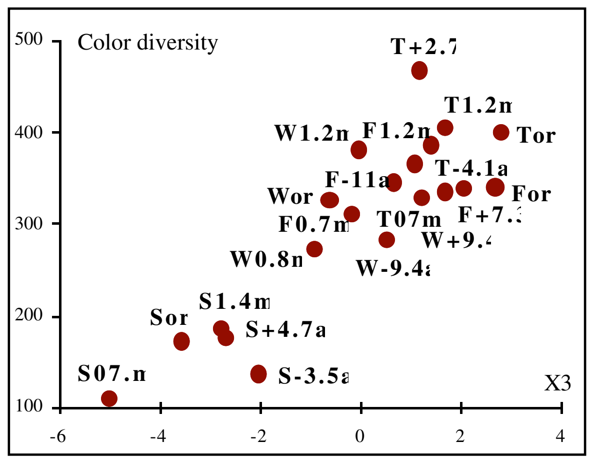

Figure 4. The experimental X3 coordinates of the images for the subject E.E. plotted versus the indices of color diversity. The color diversity for every image was calculated as a number of clusters in the CIELUV color space obtained with the ISODATA algorithm multiplied by computed average distance between these clusters(symbols: see Figure 1).

Such regular arrangement of the images along the X_3 axis confirms our assumption that this subject was able to discriminate subtle differences in colorfulness between the images based on more developed criteria that incorporate hue differences at the same time with differences in chroma and lightness. These data give further insight into the structure of the perceptual attribute of colorfulness.

Conclusions

Colorfulness of the entire image is more than one-dimensional characteristic.

The dimensions revealed in the multidimensional experiment correspond to the related to chroma parameters but also to the overall lightness and color diversity in each image.

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