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A measurement of the overall vividness of a color image based on RGB color model

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Abstract

The overall vividness of a color image is an obvious visual feature, but it is not easy to measure it quantitatively. The measurement involves the expression of the vividness of a single color and the quantitative description of a large sample of the vividness of each pixel in a color image. This paper proposes a method to roughly measure the overall vividness of a color image. The theoretically applicable color model for this method is the RGB color model. Under this color model, the vividness of a single color is given by an increasing function in terms of the distance between the color point and the grey diagonal of the color cube. When calculating the overall vividness of a color image, we first collect the vividness of each pixel in the image to obtain a frequency distribution function, and then obtain the corresponding probability mass function. Then the mean of the probability mass function is defined as the overall vividness of the color image. According to the conversions between the RGB color model and other color models, the method of overall vividness measurement can be extended to some commonly used user-oriented color models such as HSV and HSL. This paper focuses on the theoretical method of characterizing the overall vividness, rather than finding an absolute formula to calculate it. In experiments, the paper uses the sRGB color model to collect data and uses a linear function as the weight function to calculate the overall vividness of a color image.

Introduction

Many visual features of colors can be described by the existing color models. For example, some user-oriented color models use hue, saturation, and an achromatic measure relating to color brightness or intensity to describe colors. However, the visual features of a color are not limited to what the components of these color models can describe. For example, the vividness of a color is a very important visual feature, but it is not directly expressed in these color models. In the commonly used user-oriented color models such as HSV and HSL, the vividness of a single color cannot be simply represented by the saturation of the color described by these color models. Not only because the saturations of these color models are not the same, but even the set of colors with the same saturation in each model contains dark colors with low vividness.

Although there is no consensus on the definition of color vividness or a universal quantitative measurement formula to calculate color vividness, it is generally recognized as a concept closely related to the subjectively perceived colorfulness of a color by the visual system. Psychophysical experiments also indicate color vividness is mainly determined by chroma [7]. Every definition of vividness depends on the color model used and the definer's understanding of this color feature. Mostly, the definitions and measurement formulas for vividness are for a single color in different color models. In [8], the degree of vividness of a color is defined as its chromatic intensity perceived. According to this definition, achromatic colors have zero vividness and chromatic colors with high Munsell chromas have high degrees of vividness. An empirical model to compute color vividness is then given based on the observations of the Natural Colour System color chart. In [5], this empirical vividness model is adopted to propose a metric that is used to evaluate a printer's vividness. In [1], vividness is defined as a coordinate in CIELAB, based on how far a color is from the neutral black color. In [3], color vividness is described as a psychophysical color appearance attribute, and two models, namely ellipsoid-based model and hue-based model, are developed to scale the color appearances including color vividness, based on color differences under CIELAB and CIECAM02.

As for the measurement of the overall vividness of a color image, the study is mainly at the psychophysical description stage. In [11], color vividness of an image is determined by the colorfulness of each image element and the degree of contrast of the color of each image element from the colors of its surrounding image elements, where an image element is a region in the image that is of interest to the visual system. The difficulty of defining the overall vividness of a color image is finding a way to integrate the vividness of all the single colors in the image, suppose the vividness of a single color is properly defined.

This paper uses the RGB color model to define the vividness of a single color and on this basis defines the overall vividness of a color image. Although the RGB color model is implemented differently in actual applications and does not maintain the consistency of color display across devices, it is still very useful to define the overall vividness of color images under RGB due to its extensive use in commercial display devices. Moreover, Due to its special geometric property that the position of a color point in the space of the model is its color itself, mathematical expressions have more intuitive meanings. This paper focuses on explaining theoretical methods, rather than establishing an absolute standard for vividness. The proposed method can be implemented in many color models related to the RGB model. The experimental data of this paper are collected in the commonly used sRGB model.

In the RGB color model, the distance of a color point from the grey diagonal is consistent with its visual vividness. The closer the color point to the grey diagonal, the less vivid its color appears, and the farther the more vivid, so the distance to the grey diagonal can be used as a measure of the color vividness of a single color [2].

However, a color image contains a lot of colors distributed over a large amount of color pixels, and they all together trigger a subjective feeling about an overall vividness in the visual system. In early research we used the distribution of all the distances of the color pixels to the grey diagonal of the RGB color cube to qualitatively describe the overall vividness of a color image [2]. Nevertheless, using the distribution of single color vividness to describe overall color vividness of an image is inconvenient and hard for comparison.

Finding a single metric to describe the overall vividness of a color image is the motivation of this paper. An image with a weak overall vividness may not stimulate the visual system, so some subtle color details may not be well perceivable. The introduction of the concept of overall vividness can guide the design of transformations aimed at improving this visual feature. In addition, many processing techniques in color image processing, such as the techniques of color correction or tone correction, inevitably have impacts on the overall vividness of color images, but these effects have not been well considered when evaluating the processing techniques. After introducing the concept of overall vividness, we will obtain a new criterion that can be used in evaluating color image processing techniques.

Overall vividness of an image

Vividness of a single color

The paper defines the overall vividness of a color image in the RGB theoretical model. This definition needs to start with the vividness of a single color. According to [2], the vividness of a single color in RGB is determined by the distance from the position of the color in the RGB color cube to the gray centerline. Here the paper uses the same concept, but the distance is the input to an increasing function that determines the vividness value.

Suppose a color c is given in the RGB model as $c = (r, g, b)$, and d is the distance from the color point to the grey diagonal of the color cube, then

$$d = \frac{\sqrt{6}}{3}\sqrt{r^2 + g^2 + b^2 - rg - rb - gb}. \tag{1}$$

Within the RGB color cube, $0 \leq d \leq \sqrt{6}/3$. When the color c is on the grey diagonal $d = 0$, and when the color c is one of the primary RGB colors red, green, and blue, or one of the secondary RGB colors yellow, cyan, and magenta, $d = \sqrt{6}/3$.

For a given color c with distance d to the grey diagonal, define its vividness V_c as

$$V_c = f(d), \tag{2}$$

where f is an increasing function that maps the interval $[0, \sqrt{6}/3]$ to the interval $[0, 1]$, then the vividness is normalized to the range between 0 and 1. The function f is increasing in terms of d is based on the belief that the closer a color to the grey diagonal the less vivid the color is, and the farther a color to the grey diagonal the more vivid the color is. A proper function f could be derived from the corresponding psychophysical studies, but this is not under the discussion of this paper. For demonstration, the paper uses the linear function $f(d) = \left(\frac{\sqrt{6}}{2}\right) d$ that normalizes d to the interval $[0, 1]$, and gets a formula for the vividness for a single color $c = (r, g, b)$ in the following equation,

$$V_c = \frac{\sqrt{6}}{2} d = \sqrt{r^2 + g^2 + b^2 - rg - rb - gb}, \tag{3}$$

Equation (3) gives a vividness value 1 to the three primary RGB colors and the three secondary RGB colors. Also, by the formula, a grey color with the same r, g, and b components has a vividness value 0. All other vividness values of single colors are between 0 and 1.

To visualize the concept, place the RGB color cube in the way that its grey diagonal is vertical. The colors with the same vividness form a round cylinder surface, as illustrated in Figure 1. The shape of the cylinder surface is restricted in the RGB color cube, and its area within the RGB color cube changes along with its radius. Since the cylinder is restricted inside the color cube, the top and bottom intersections with the color cube are pieces of ellipses, and its measure along the grey diagonal is inversely proportional to its radius.

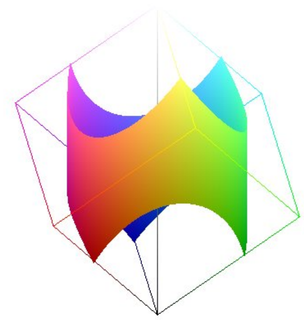

Figure 1. A cylinder surface with colors of the same vividness, restricted in the RGB color cube. The radius of the cylinder is 0.5. By equation (3), the vividness of each single color in the cylinder is about 0.612373.

Figure 2 shows the unfolded surfaces of three cylinders, scaled to the same length. From top to bottom, their corresponding radii are 0.1, 0.3, and 0.5, respectively. After normalization by equation (3), they respectively represent those colors with vividness 0.122474, 0.367423, and 0.612373. The colors on each surface have the same vividness value. The bigger the value, the more vivid the colors are.

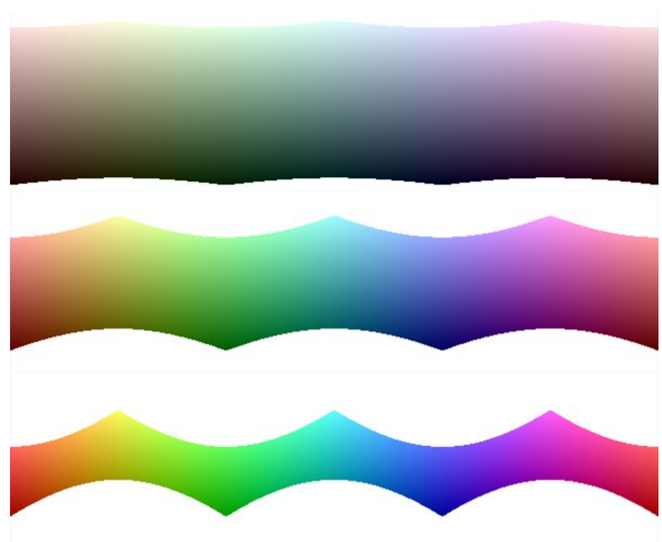

Figure 2. Unfolded surfaces of three cylinders restricted in the RGB color cube, scaled to the same length. The colors on each surface have the same vividness. Top. The unfolded cylinder with radius 0.1, with a vividness value 0.122474 on all the colors in the surface. Middle. The unfolded cylinder with radius 0.2, with a vividness value 0.367423 on all the colors in the surface. Bottom. The unfolded cylinder with radius 0.5, with a vividness value 0.612373 on all the colors in the surface. Vividness is calculated with equation (3).

An overall vividness measurement

Because there is a large amount of single color vividness values involved, using statistical method to define the overall vividness of a color image is a natural way.

For a color image considered in the RGB color model, we collect the distances to the grey diagonal of the color cube of all the pixels, and then convert the distances to the vividness with equation (2). In other words, we compute the vividness of the color of each pixel to get a set of vividness values. Based on this data, a frequency distribution of the vividness values can be obtained. The distribution of the vividness is over the interval $[0, 1]$ that is evenly divided into a predetermined number of bins. In this paper, for demonstration, equation (3) is used to get the frequency distribution of the vividness over the interval $[0, 1]$ that is divided into 1000 bins. Then, the corresponding relative frequency distribution of the vividness is calculated by dividing each frequency by the total frequencies.

Generally, we partition the vividness interval $[0, 1]$ into n even subintervals and use these n subintervals as bins to distribute the relative frequencies of the vividness of single colors. For this purpose, we introduce a discrete variable V that takes values at $v_i = i/n, i = 1, 2, 3, \cdots, n$. Then we define a probability mass function based on the relative frequency distribution of the vividness. Denote this probability mass function $p(V)$ and assign $p(v_i)$ the relative frequency of the vividness of the i-th bin. Note that the vividness interval $[0, 1]$ is discretized into n values $v_i = i/n$, $i = 1, 2, 3, \cdots, n$, but 0 is not included. This would not be an issue for a color image when n is big enough.

For a color image I under the RGB color model, suppose the probability mass function $p(V)$ is obtained as in the above. Define the overall vividness V_I of the image as the mean of the probability mass function,

$$V_I = \sum_{i=1}^{n} v_i p(v_i) = \sum_{i=1}^{n} \frac{i}{n} p\left(\frac{i}{n}\right). \tag{4}$$

This definition well matches the vividness of a single color if the color image has only one color c. Suppose the vividness of all the pixels fall in the i-th bin of the relative frequency distribution of vividness, then $V_c \approx i/n$. Also, $p(v_i) = 1$ and all other p values are equal to 0. Then by equation (4), the overall vividness of the image with the single color is $V_I = i/n$, which matches the vividness of this single color when n is large enough.

The definition of the overall vividness of a color image is done in a statistical sense. Equation (4) is the mean of the relative frequency distribution of the vividness of single colors in a color image. Another closely related statistical term the variance is also worthy of attention:

$$\sigma^2 = \sum_{i=1}^{n} (v_i - V_I)^2 p(v_i) = \sum_{i=1}^{n} v_i^2 p(v_i) - V_I^2 = \sum_{i=1}^{n} \left(\frac{i}{n}\right)^2 p\left(\frac{i}{n}\right) - V_I^2. \tag{5}$$

Statistically, the variance measures the dispersion of the single color vividness. It works together with the overall vividness to quantitatively describe an important color feature in an image. Its effect could be studied through psychophysical experiments, and it is not currently under the discussion of this paper.

Vividness in HSV and HSL color models

With the conversion relationships between the RGB color model and other color models, the overall vividness measurement can also be used under some user-oriented color models, such as the color models of HSV and HSL. In this way, the impact of image processing techniques on the vividness can be directly detected in these models.

The measurement of the overall vividness of a color image in either HSV or HSL is the same as what is defined in equation (4) for the RGB color model. However, the distance function in equation (1) that is used to define the vividness of a single color given by equation (2) should be rewritten in terms of the new components in HSV or HSL.

Let us look at the HSV color model first. The original hexagonal HSV color model has three components Hue, Saturation, and brightness Value, which are all normalized into the interval $[0, 1]$. If a color $c = (h, s, v)$ is in the space of HSV, a piecewise conversion function with six pieces on the Hue component h can be used to convert it to the RGB color (r, g, b) [9]. Take the piece of $0 \le h < 1/6$ as an example. With a calculation by equation (1), the distance from the color point to the grey diagonal of the RGB color cube is expressed as

$$d = \frac{\sqrt{6}}{3} sv\sqrt{1 - 6h + 36h^2}. \tag{6}$$

The vividness of the color can also be expressed in terms of h, s, and v. When $0 \le h < 1/6$, the vividness formula in equation (3) can be expressed as

$$V_c = sv\sqrt{1 - 6h + 36h^2}. \tag{7}$$

It is easy to find that the minimum value of the quadratic expression $1 - 6h + 36h^2$ is $3/4$ and its maximum value is 1 when $0 \le h < 1/6$, then the fluctuation of the factor $\sqrt{1 - 6h + 36h^2}$ in equation (7) is roughly between 0.866 and 1, with a relative change less than 13.4%. The situation is the same for the other pieces of h. This implies that under the HSV color model, the influence of the Hue component to the color vividness is small. The influences from the other two components brightness Value and Saturation can be much bigger.

It is also worth noting that a commonly used tone correction technique under the HSV color model is to transform the achromatic component to change the color contrast of a color image. This method aims to maintain the chromaticity determined by Hue and Saturation. Seen from equation (7), when the brightness Value represented by v changes, the vividness of a single color changes accordingly, which inevitably changes the overall vividness of the color image. This well explains why the color of the image transformed by tone correction is perceived to be significantly different by the visual system under the condition of maintaining the chromaticity information. This is because the overall vividness of the image has changed. In addition, it can also be seen from equation (7) that a change to Saturation represented by s also affects the vividness of a single color, thereby affecting the overall vividness of the image.

The situation is similar under the HSL color model. In the original design of HSL model [4], a piecewise function with six pieces of the Hue component is used to convert a color $c = (h, s, l)$ to the corresponding RGB color (r, g, b). The components h, s, and l are normalized to the interval $[0, 1]$. Consider the piece of $0 \le h < 1/6$ as an example, with the conversion formula given in paper [4], the vividness of the single color $c = (h, s, l)$ can be computed with equation (3), giving the following formula when $0 \le l < 0.5$,

$$V_c = 2sl\sqrt{1 - 6h + 36h^2}, \tag{8}$$

or the following formula when $0.5 \le l \le 1$,

$$V_c = 2s(1 - l)\sqrt{1 - 6h + 36h^2}. \tag{9}$$

Expressions for the other pieces of h can be obtained in similar ways.

With a similar analysis as that for the HSV color model, under the HSL color model the vividness of a single color is greatly influenced by its Saturation and Lightness but just slightly affected by its Hue. Any hue preserving transformation on a color image under the HSL color model inevitably changes the overall vividness of the image through Lightness, or Saturation, or both.

Experimental results

The focus of this paper is on the theoretical aspects. Which kind of increasing function f in equation (2) has an optimal reflection to the perception of color vividness is not considered in the paper. In demonstrations, we use equation (3) as the definition of the vividness of a single color in the RGB color model. To calculate the overall vividness of an image, we use $n = 1000$ in equation (4). The sRGB color model is used to collect data for calculations.

The images shown below are all copied from the electronic version of some color image processing research papers in PDF format, and the images are all saved in JPEG format. These images are then used in experiments for demonstration. The images shown here have been reduced in size to facilitate arrangement. The purpose of the demonstration is to show how the overall vividness of a color image changes during the image processing, and it can reflect the nature of the processing method itself.

Figure 3 displays some of the images copied from paper [6]. That paper uses a contrast enhancement algorithm to improve the visual qualities of images under the RGB color model. Figure 3 (a) shows the original image "Candies", Figure 3 (b) and Figure 3 (c) are resultant images of the algorithm with different parameter settings. Also, these two resultant images roughly keep the ratio of R/G/B as in the original image to preserve the chromaticity. Figure 3 (d) is the result of an existing algorithm for comparison.

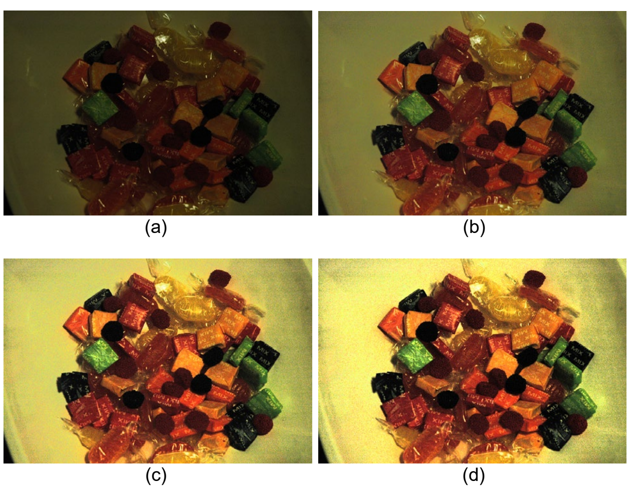

Figure 3. Images copied from paper [6]. (a) The original image "Candies". (b) A resultant image after processing. (c) Another resultant image with a different parameter setting. (d) The resultant image by an existing algorithm.

The values of the overall vividness of these images are listed:

Figure 3 (a): 0.120
Figure 3 (b): 0.234
Figure 3 (c): 0.369
Figure 3 (d): 0.389

Paper [6] aims to improve its own specific metrics, but we can see its method also enhances the overall vividness of the original image. With the metrics that paper [6] is interested better than those of Figure 3 (d), the overall vividness of Figure 3 (c) is also very close to that of Figure 3 (d).

Figure 4 displays some of the images copied from paper [10]. Figure 4 (a) shows an original image (image credit: J. L. Lisani CC BY) that contains pixels with oversaturated colors, for example, some areas on some blue balls. Figure 4 (b) is the resultant image by the algorithm proposed in paper [10] for its specific purposes. The processing is under the RGB color model. Figure 4 (c) is the resultant image by an existing method for comparison.

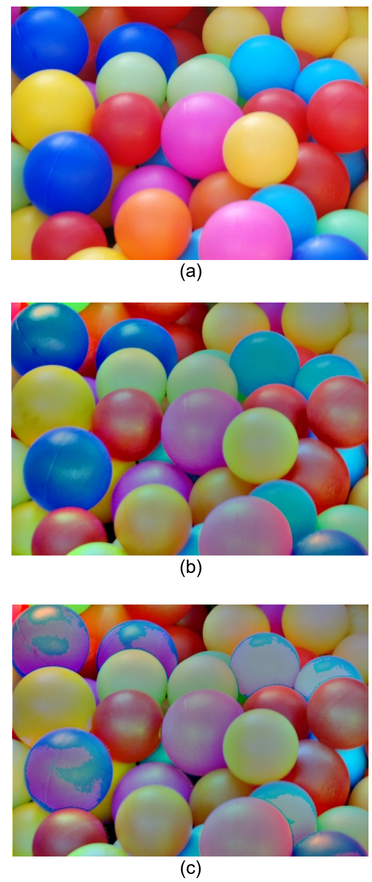

Figure 4. Images copied from paper [10]. (a) An original image containing pixels of saturated colors. (b) The resultant image by the algorithm proposed in paper [10]. (c) The resultant image by an existing method.

The comparisons of the overall vividness of these images are listed in the following.

Figure 4 (a): 0.541
Figure 4 (b): 0.371
Figure 4 (c): 0.261

The method in paper [10] not only solves the problem of color oversaturation better, but also the overall vividness of the resultant image is closer to the original image.

The images in Figure 5 are from paper [2]. Among them, the images of Figure 5 (a), Figure 5 (c), and Figure 5 (e) are original images (image credit: R. C. Gonzales and R. E. Woods). Paper [2] is dedicated to improving the overall vividness of a color image by transforming S and V simultaneously in the HSV color model. The resultant images are displayed in Figure 5 (b), Figure 5 (d), and Figure 5 (f), respectively. However, the overall vividness in paper [2] is only described qualitatively, and no quantitative measurement is made. The new definition of this paper is used here to assign numerical values to the overall vividness of the images to illustrate the effectiveness of the transformations with numbers.

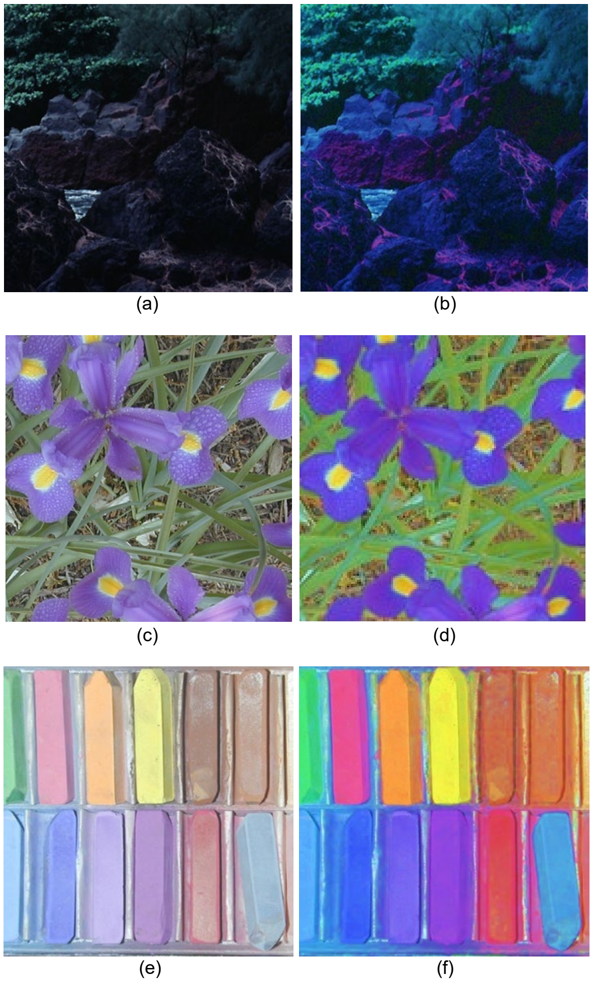

Figure 5. Images copied from paper [2]. (a) An original image with a dark tone. (b) Overall vividness enhanced image of the image in (a). (c) An original image with a flat tone. (d) Overall vividness enhanced image of the image in (c). (e) An original image with a light tone. (f) Overall vividness enhanced image of the image in (e).

The overall vividness values of these images are obtained:

Figure 5 (a):	0.055
Figure 5 (b):	0.250
Figure 5 (c):	0.172
Figure 5 (d):	0.360
Figure 5 (e):	0.172
Figure 5 (f):	0.485

Numerically, we can see how much is improved in overall vividness on each original image. What is particularly interesting is that the images in Figure 5(c) and Figure 5(e) have the same overall vividness, but since they have different tones, they are processed differently, resulting in different overall vividness. From the numerical values, the overall vividness of the image in Figure 5(f) is better than that of the image in Figure 5(d). This implies the transformation used on the type of images represented by Figure 5(e) improves the overall vividness better for that type of images.

Conclusions

The overall vividness of a color image is an important color feature. In a color model, statistical methods can be used to assign the overall vividness a numerical value, to facilitate the measurement and comparison of this color feature. In this paper, the vividness of a single color is defined in the RGB model with a calculation formula, and then the overall vividness of a color image is defined as the mean of the probability mass function of the vividness of all the single colors in the image. This definition gives a numerical measure of this visual characteristic of a color image, which facilitates the comparison of different images on vividness. In addition, this metric can be used to evaluate the performance of image processing techniques in this regard. According to the corresponding conversion relationships, the vividness of a single color and the overall vividness of an image can be directly used in other models such as HSV and HSL, to evaluate the effect of image processing techniques in these models on overall vividness.

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