COLOR CONTRAST METHOD BASED ON SUBJECTIVE WARMTH AND COLDNESS

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The developed method for assessing the warmth-coldness allows us to determine the ranks for the entire range of the sRGB color gamut with accuracy 4% with a relatively small number of studies. The model calculated based on the method allows us to estimate the ranks of intermediate colors that are not involved in testing. At the same time, the accuracy of the model when using third-order approximation allows us to ensure accuracy comparable to the accuracy of the experimental results. Optimization of the path of traversal of the color space allows us to reduce the influence of high-frequency noise, while maintaining the path from cold shades to warm ones. The color contrasting method based on warmth-coldness shows results that significantly exceed the results of previously developed algorithms. This method is suitable for use in security and medical applications where it is necessary to highlight invisible details in a grayscale images, for example in radiography. In order to achieve better quality of applied systems, their sensors can have parameters and characteristics that differ from those of the human visual system, which can make it fundamentally impossible to form realistic controlled images. This article discusses a method for subjective assessment of color thermal-coldness with an extended range based on an inaccurate model. By iteratively refining the results in 6 stages, a third-order model was created and approximated for use in color contrasting. Based on the model, a simplified color contrasting method was developed, which was further optimized using an upgraded annealing method. As a result, an improved color contrasting method was created, significantly exceeding the characteristics of similar methods.

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Introduction

While in broadcast television systems the main criterion of image quality is its realism, assessed, for example, by preference in the process of performing subjective-statistical examinations, the criteria of the quality of work of applied television systems, which provide for visual control of images by the operator, can often be different. These may include the probabilities of errors of the first and second kind when detecting certain objects or events, the operator's reaction time to events and the degree of his fatigue, associated with the complexity of the structure of the controlled images and the visibility of the controlled objects, including that associated with the absolute or relative contrast of these objects. In order to achieve better quality of applied systems, their sensors can have parameters and characteristics that differ from those of the human visual system, which can make it fundamentally impossible to form realistic controlled images.

Most often in applied television systems relative to the human visual system, spectral characteristics are changed, which allows for better contrast of objects (for example, in spectrozonal systems) or obtaining information that is not available for direct observation [21, 24, 25] (for example, in lidar, bolometric systems, radiography, electron microscopy, polarimetry, etc.). The output data of such systems are one or more images in grayscale. Since human vision is capable of perceiving about two hundred different gradations of brightness within a limited dynamic range even under optimal conditions, in many cases this is a limitation, since the visualized data may have a larger dynamic range or a larger number of significant gradations of brightness.

Considering that displaying the original color information in the considered cases typical for applied systems is impractical or even impossible, color information is often used to visualize images in conventional colors. The fact is that human vision has three independent x color channels, each of which has the above limitations on perceived contrast and the number of gradations of stimulus intensity, thus, theoretically, using color coding, it would be possible to increase the total number of perceived gradations n_0 to $n_0 = n_R n_G n_B$, where the letter indices correspond to the red, green and blue channels. A well-known and obvious disadvantage of such a solution is the loss of resolution - it is known that the color resolution of the human visual system is significantly, approximately an order of magnitude, lower than that of brightness [3], however, a decrease in the gain from using color coding of information by an order of magnitude still leaves it quite high.

The first color contrasting systems of images created in the era of analog television were optimized not so much for the efficiency of information perception, but for the ease of implementation [7, 15, 18]. The algorithm for converting a black-and-white image into a pseudo-color one, the so-called color encoding algorithm, can be visualized by depicting a line of detours of points of a color body (or plane), for example, in the x, y, Y color space [8]. By dividing the specified detours line into equal sections so that the number of section boundaries corresponds to the number of brightness gradations of the original image, the coordinates of each of the boundary points of the detours line sections will give the coordinates of the color to which the encoded brightness value will correspond.

It should be noted that in digital image processing, the shape of the detours line does not affect the complexity of image processing, since a table of correspondence between the input and output brightness/color values is technically calculated, therefore modern color contrasting algorithms are somewhat more complex in terms of concept than earlier ones, but this does not affect the complexity of information processing. The evaluation of the efficiency of color contrasting is usually performed subjectively, by presenting test images to subjects who must determine the presence of certain low-contrast details.

This procedure is not standardized, but can generally be performed under the conditions described in recommendation [1]. [2] also proposes a test image that allows us to evaluate the effectiveness of color coding at all brightness levels of the original image. It consists of two gradation wedges joined together in such a way that the difference in their brightness at the transition boundary is one unit, i.e.

$$L(x,y) = \begin{cases} x, & y < \frac{y_{\max}}{2} \cup x \le L_{\max} \\ x-1, & y \ge \frac{y_{\max}}{2} \cup 1 \le x \le L_{\max} \\ L_{\max}, & x > L_{\max} \\ 0 & \text{otherwise} \end{cases}$$

where $L_{\max}$ is the maximum pixel brightness value, x and y are coordinates.

A common disadvantage of known color contrasting methods [12, 19] is that information about the original image intensity is not reflected in the final result, although it is often important for interpreting the output data. In addition, if the task of color contrasting an image is set in the traditional way, that is, to perform a traversal of the color body in such a way that the distance between adjacent points is maximum, while the distance between points in the color space is proportional to the distance between them on the traversal line, the resulting image often contains "unexpected" color transitions (artifacts) that create false boundaries and mask objects instead of contrasting them. In addition, given the many ways of drawing the traversal line, this problem cannot be solved optimally today, at least by direct enumeration. Given the indicated disadvantage, it is advisable to introduce additional restrictions in the optimization problem formulated above.

In general, even if the original image intensity values are rejected, a person is able to estimate the value of the color-coded quantity. This practice is used to visualize in conventional colors functions, the number of dimensions of which is greater than the visualization tools allow to display [11, 14]. Such solutions can be seen, for example, in the color indication of some parameters, in the display of heights on geographical maps, visualization of function graphs. Usually, smooth color transitions are used to visualize such data, which the authors choose based on personal preferences.

However, there is a color scale that many people interpret quite unambiguously in the values of the value encoded in it - the scale of heat and cold [2]. It can be assumed that the idea of this scale appeared in humans in the process of their life, possibly over generations – warm colors are considered to be approximately the color of the flame of a fire, while cold colors are well described by the color of snow reflecting a clear sky, which can be observed in the northern hemisphere in winter during the action of the Arctic anticyclone. It should be noted that in general the scale of heat-coldness, as follows from the description above, is subjective, and in fact the color of the radiation of an absolutely black body, depending on the temperature, changes inversely proportional to the subjective ideas about its heat, that is, the color of the radiation of an absolutely black body, which a person would consider the coldest, corresponds to its maximum temperature and, conversely, warm colors correspond to relatively low temperatures of the radiation of an absolutely black body.

Thus, using the human ability to sort colors by heat-coldness, it is possible to encode information about the intensity of a value in color so that it can be subsequently interpreted. To do this, it is necessary to sort all the displayed colors by the criterion of heat-coldness, that is, to create a mathematical model of the subjective sensation of the warmth of colors.

The first stage of creating this model is obviously the collection of data, which should be a sorting of all colors perceived by a person by the criterion of heat-coldness [9, 10]. However, even if we do not use all colors perceived by humans, but limit ourselves to the values of the sRGB color space used in most display devices, then with eight-bit quantization we will have to sort 2563 values. On the other hand, following the recommendation [itu500], the duration of the evaluation session should not exceed 30-40 minutes, and the evaluation time of each pair should be 5-10 seconds.

Considering that it is advisable to test each subject in one session, which eliminates the need to take into account the influence of the mental and physiological state of the subjects and similar factors on the assessments, it is obviously impossible to perform a complete enumeration of colors during testing. However, taking into account the possibility of using fast sorting methods and Grassmann's second law "With a continuous change in radiation, the color of the mixture also changes continuously" [22], it is possible to solve the problem of conducting subjective-statistical examinations and obtaining results with an accuracy that can be estimated.

At the same time, in many applied problems, it is not necessary to transmit an image while preserving all its characteristics. But it is important to preserve certain parameters. In particular, in medical and security systems, image contrast has a higher priority than color. Therefore, many cameras in these areas are black and white, since it is easier to implement high contrast in such cameras while maintaining other characteristics at a sufficient level. For example, in medical systems, camera size is often key to being able to use it in limited spaces, and small size is associated with a decrease in contrast.

In monitoring tasks, the final recipient of information is often a person, so an important task is to ensure the required subjective parameters. In some cases, when using low-contrast images, the required parameters are present in the television signal, but are not captured by the human visual system [13]. Therefore, the task of image transformation with the allocation of the necessary parameters is relevant.

If the original image does not contain color information or it is not important for solving the problem, you can use color to increase the contrast of the image even if these colors do not match the original. This technology is called color contrasting in pseudo colors. The choice of colors is key to successful contrasting. This article is devoted to the choice of colors for high-quality contrasting of images using subjective thermal coldness.

The first part presents a method for determining thermal coldness for the entire sRGB color gamut, the initial colors are indicated taking into account the capabilities of the subjects.

The second part examines the experimental results, analyzes them, determines the accuracy of the experimental data, builds an approximation model, and defines the scope of application.

The third part presents two methods for determining color contrast. The first is simplified based on the ranks of color coolness, and the second is optimized using the annealing method.

In conclusion, conclusions are drawn on the work.

Definitions of subjective warmth-coldness

Method

The method for determining the warmth-coldness of colors is based on pairwise comparison of colors by subjects with the identification of a warmer shade. Since putting the colors in the correct order requires a large number of tests, and the subjects in this case get very tired and the quality of the study is noticeably reduced, a combined iterative algorithm was used, allowing experiments to be carried out in several stages, gradually refining the results.

The initial order was randomized to equalize of error between colors [5]. Each stage is carried out on a separate day, if possible with new subjects, which increases the accuracy of the experiment.

At the first stage, an experiment is carried out with a small number of color shades, on the basis of which an inaccurate assistant model is created, allowing relatively accurate comparison of colors that are confidently very different in warmth-coldness. The peculiarity of the model is the ability to use the rank of a close color when assessing the warmth-coldness, which allows it to be effectively used when conducting an experiment with a larger number of colors than those in the model.

At each subsequent stage, the model obtained at the previous stage is used to relieve the subject from answering previously known questions, due to which additional colors can be added to the experiment while maintaining the number of tests.

At the last stages of the experiment, new colors are not shown to the subjects, but due to the more accurate model, the number of experiments is reduced. Due to this, the subjects are less tired, which gives more accurate results that can be used in practice.

Synthesis of the initial data

The purpose of the experiment is a subjective comparison of colors by warmth-coldness, which is supposed to be carried out for the entire sRGB color space, since the results of the experiment are supposed to be used in the problem of color contrast for display on monitors, which in most cases have exactly this color gamut. However, this color space has approximately 16 million colors [20, 23], which makes the task of subjective assessment very long.

Since the dependence of subjective warmth and coolness on color is continuous, it is possible to use some colors with subsequent interpolation without significant deterioration in the quality of the results. In [2], the process of choosing colors using the CIE Lab color space with a step of 11, providing a good balance between accuracy and the number of experiments, is described.

However, in this study, all colors have the same brightness, which leads to certain disadvantages of the model. Firstly, color contrast methods using brightness along with chroma have certain advantages [16, 17]. Secondly, using only brightness significantly reduces the color gamut.

Therefore, the method from [2] was used to synthesize the initial data, but it was expanded for use with different brightnesses.

Unfortunately, this increases the number of experiments, so it was decided to conduct several stages of testing using an intermediate model after each test to maintain the number of tests while increasing the colors.

The first and second stages are carried out at the average brightness of the monitor and allow you to create a model for one brightness. The third and fourth stages are carried out with an expanded grid, but with successive addition of color space sections of lower and higher brightness.

The sixth stage is carried out with a grid with a step of 11 for the entire range of brightnesses.

The seventh stage is equivalent to the sixth, but with a reduced number of tests to increase the accuracy of each experiment.

Table 1

Number of colors for each experiment

Stage	1	2	3	4	5	6
Step	11	11	15	15	11	11
Number of brightneses	1	1	3	5	13	13
Number of colors	135	135	169	214	786	786
Number of tests	675	675	1014	1284	5502	5502

Experiment results

Analysis of results

During each stage of the experiments, the condition of the subjects was assessed. As a result, it was concluded that a person can pass up to 1000 tests poorly and up to 400 tests well enough. Adding more tests would result in incorrect regions of interest [4] and poorer quality data. The concept of quality means that when conducting additional tests, the maximum error (confidence interval at the level of 0.95) decreases. Thus, the results were considered high-quality if 10 tests reduced the error by 20%.

At the same time, at each stage it was necessary to maintain a certain ratio of quality and quantity of tests. Thus, stages 1, 3, 4, 5 provided primary data, and more time was included in them for one subject. At stages 2 and 6, the task was to refine the model, so a smaller number of tests were included there.

Each stage was carried out until the model became accurate enough to comply with the required number of tests for the next stage. The resulting number of tests, as well as the maximum error at each stage are given in Table 2.

Table 2

The resulting parameters of each experiment stage

Stage	1	2	3	4	5	6
Number of tests (real)	675	370	900	800	900	400
Maximum error, %	7	5	8	8	7	4

Model

Despite the large number of colors in the test, it is necessary to expand the task to the entire sRGB space. For this purpose, a three-dimensional polynomial regression was performed and a model in xy coordinates was obtained. Since the experiment was also conducted for different brightnesses, the brightness was also taken into account. Different options were considered and it turned out that the most convenient way to consider the brightness is as the average value of R, G and B. This value is further designated as I in the article. In this case, the maximum degree of the polynomial is 3, since this is a sufficient degree to achieve accuracy comparable to the accuracy of the experiments (4%). In this case, accuracy was defined as the maximum deviation of the model from the experimental results relative to the maximum rank.

$$\begin{aligned} R = & -1.77 + 15.5x + 3.09y + 2.92I - 6.7x^2 - 65.7xy + \\ & +19.5y^2 - 21.6xI + 1.95yI - 1.09I^2 - 2.21x^3 + 40.1x^2y + \\ & +34.3xy^2 - 21.5y^3 + 6.06x^2I + 12.3xI^2 - 10.9y^2I - \\ & -5.6yI^2 + 32.7xyI - 0.88I^3 \end{aligned} \tag{1}$$

The figure shows the contour images of the obtained model for different brightnesses from 30% to 70% of the maximum screen brightness. It follows from the model that blue shades are perceived as the coldest, and orange shades are perceived as the warmest. At the same time, brightness has little effect on the perception of warmth and coldness, but there is a slight effect, which is manifested in a faster increase in the warmth of the tone at higher brightness. Thus, in cold shades, light colors seem colder, and in warm shades – warmer.

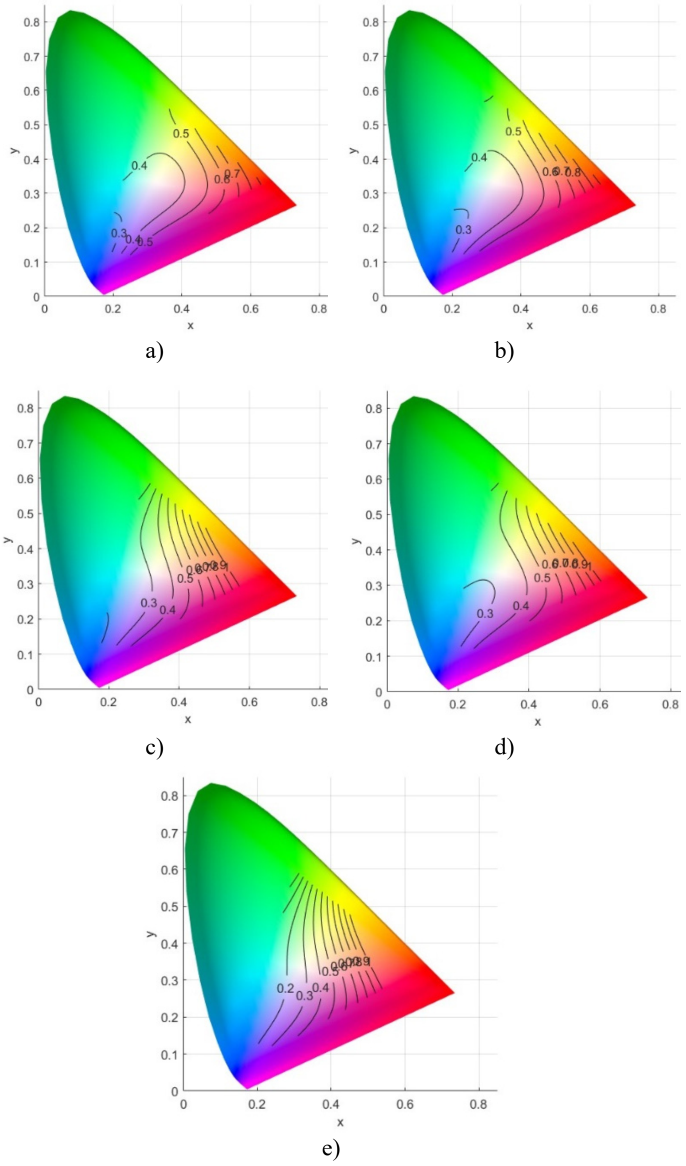


Fig. 1. Contour graphs of the model depending on brightness (a – 30%; b – 40%; c – 50%; d – 60%; e – 70%)

Developing a LUT table for color contrast

Choosing color shades

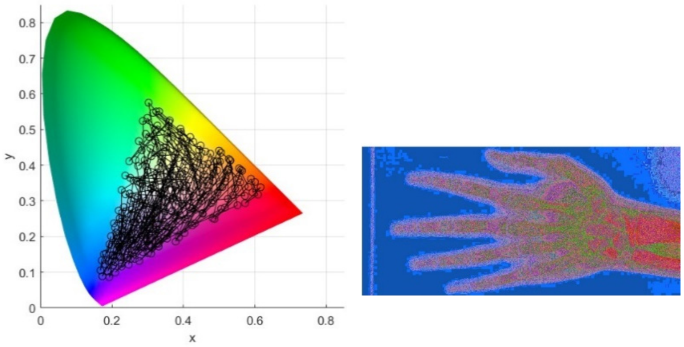
Color contrast requires the use of a number of shades of gray equal to the number of shades of gray in the original image. In most cases, this is 256, so this case is considered in this paper. Since the color model calculated based on the experimental results turned out to be quite accurate, it is possible to use any color shades within the model range. In this case, it is possible to use brightness from 30% to 70% of the monitor and any colors in the sRGB gamut within these brightnesses. The brightness restrictions are due to the fact that outside the specified range, the model becomes less accurate.

As in the case of choosing colors to determine warmth and coldness, when choosing shades, it is necessary to use an isotropic color space from the point of view of perception, so the CIE Lab space was chosen.

In this space, colors in the specified range were chosen at an equal distance due to the features of the space. Since 256 shades are required, the distance between the colors was chosen equal to 13 for three brightness levels: 37%, 50%, 63%.

Matching Shades Taking into Account Warmth-Coolness

Each of the resulting shades was assigned a warmth-coolness rank according to the model described above. The colors were then sorted by the resulting rank. After that, each of the 256 grayscale gradations in the low-contrast image was matched with a color with the corresponding index. Thus, black was matched with the coldest element, and white with the warmest. The resulting path is shown in the image.



a) b)

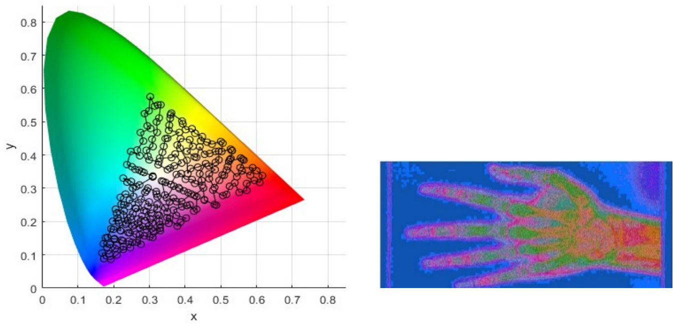
Fig. 2. The way to use simple rank increase

The obtained results show that this method allows contrasting certain objects, but the path by simply increasing the warmth and coldness does not provide sufficient image contrast. Moreover, this option leads to high-frequency noise that masks certain details, which significantly worsens the quality of the method [6].

From the color sequence, it is clear that the main problem is that colors with the same color temperature can be located in different areas of the color space, which often leads to the path making sharp transitions to one tone in another part of the spectrum and back (with the same subjective color temperature).

This problem can be solved by reducing the "color" length of the path from cold to warm, while maintaining the direction of increasing warmth. The temperature can be reduced by the annealing method, which easily copes with the task of reducing the length of the path. In addition, this method is a gradual improvement method, so some initial value is supplied to the input. Usually, such a value becomes a random path, but in this case there is already a method that needs to be improved, so it is advisable to specify the above method as the initial value. In addition, the main idea of the work is to create a contrasting method based on warmth and coldness, so it is necessary to preserve the transition from cold to warm.

This can be ensured by two mechanisms. The first mechanism is to preserve the initial (for black) and final (for white) shades. Thus, when solving the problem of finding the minimum path, the initial and final points are fixed. The second mechanism is to add a coefficient of warmth and coldness so that the path by decreasing warmth would be considered less favorable. Thus, the length of the path is equal to the product of the distance between the color shades in the CIE Lab space and (1 – the difference in warmth and coldness).



a) b)

Fig. 3. Path taking into account the annealing mechanism

The annealing algorithm allowed us to reduce the length of the color path by 4 times, which reduced the number of intersections and ordered the path in the color space. As a result, color contrast became much more noticeable.

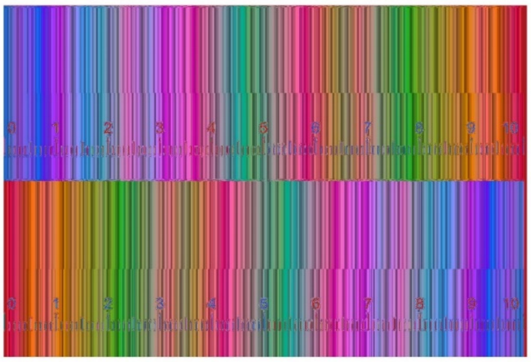


Fig. 4. Test image with color contrast

To quantify the algorithm's performance, a gradation wedge with a scale and a 1-pixel offset is used. Image analysis shows that across the entire brightness range, the method allows for high-quality separation of adjacent shades in approximately 90% of cases, making it the most effective of the algorithms under consideration.

Table 3

Comparison of algorithms

№	Algorithm	Efficiency
1	Stigma	0.29
2	Circular, 2 circles	0.23
3	Spiral-triangiular	0.43
4	Equal-contrast	0.67
5	Warmth	0.9

Conclusions

The developed method for assessing the warmth-coldness allows us to determine the ranks for the entire range of the sRGB color gamut with sufficient accuracy (4%) with a relatively small number of studies.

The model calculated based on the method allows us to estimate the ranks of intermediate colors that are not involved in testing. At the same time, the accuracy of the model when using third-order approximation allows us to ensure accuracy comparable to the accuracy of the experimental results.

The coefficients of the calculated model allow us to conclude that color coolness depends on the color tone much more strongly than on the brightness, while the brightness increases the difference in warmth-coldness between close shades.

Direct use of warmth-coldness ranks for color contrasting allows us to highlight low-contrast areas, but introduces high-frequency noise, which degrades the quality of the algorithm.

Optimization of the path of traversal of the color space allows us to reduce the influence of high-frequency noise, while maintaining the path from cold shades to warm ones.

The color contrasting method based on warmth-coldness shows results that significantly exceed the results of previously developed algorithms.

This method is suitable for use in security and medical applications where it is necessary to highlight invisible details in a grayscale images, for example in radiography.

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МЕТОД ЦВЕТОВОГО КОНТРАСТИРОВАНИЯ НА ОСНОВЕ СУБЪЕКТИВНОЙ ТЕПЛОХОЛОДНОСТИ

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Аннотация
В данной статье рассматривается метод субъективной оценки теплохолодности цветов с расширенным диапазоном на основе неточной модели. Благодаря итерационному уточнению результатов за 6 этапов создана и аппроксимирована полиномиальной регрессией третьего порядка модель восприятия теплохолодности для использования в цветовом контрастировании. На основе модели был разработан упрощённый метод цветового контрастирования, который в дальнейшем был оптимизирован с помощью модернизированного метода отжига. В результате был создан улучшенный метод цветового контрастирования, значительно превышающий характеристики аналогичных методов.

Ключевые слова: *метод цветового контрастирования, теплохолодность цветов, sRGB*

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