https://doi.org/10.2352/issn.2169-2629.2021.29.71

Image Enhancement for Colour Deficiency via Gamut Mapping

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Abstract

This paper describes a colour image enhancement method for those having colour-vision deficiencies. The proposed method can be divided into 3 stages. Firstly, a conversion relation between the wavelength shift (measured in nanometers) of a colour deficient observer (CDO) and the severity of colour deficiency was established. Secondly, the perceived colour gamut was built by applying the conversion relation. Finally, the original images were re-coloured by adopting a gamut mapping algorithm to map colours from the gamut of colour normal observer (CNO) to that of a CDO. Psychophysical experiments were then conducted to show the effectiveness of the method.

Introduction

The colour perception for a CNO depends on three kinds of photoreceptors, *i.e.,* the L, M, and S cones, mainly differentiated by their varying peak wavelengths [1]. Types of photopigments were different in the cones and they contribute to the corresponding cone responses.

However, these photoreceptors for a CDO, are somehow different from those for a CNO by either inherited or acquired. There are three kinds of CDOs called protanomals, deuteranomals, and tritanomals, associated with their corresponding impaired cone, *i.e.,* the L, M, or S cone respectively. Further, if one cone type is lacking, the observer was then called a dichromat or more specifically, a protanope, deuteranope, or tritanope according to the missing cone.

From previous studies [2], we can find that approximately 7.9% of males and 0.42% of females suffer from either color vision defects, which equals to more than 200 million people globally. Hence, it is of great influence to those CDOs if one can help to re-build their colour perceptions.

Many researchers endeavored in this area and proposed many colour enhancement methods for CDOs when viewing images on a display. According to the CIE technical report [3],these methods can be divided into 3 major categories, *i.e.,* recolouring, edge enhancement and pattern superposition.

Recolouring is the most common techniques in this field. Its aim is to replace the easily confused colours with more distinguishable ones so as to help CDOs discern colours. Lau et al. [4] developed a smartphone app that enables color deficient users to visualize problematic color contrasts. They applied a colour transform that shears the data along lines parallel to the dimension corresponding to the affected cone sensitivity of the user and claimed that this app can help CDOs distinguish colours such as red and green apples. This kind of method is quite effective for CDOs to view images and can offer more freedom to fine-tune the perceived colours. However, additional manual operations are unavoidable for this kind of method and it cannot be further extended to other applications such as colour enhancement for videos. Sakamoto [5] described a colour enhancement method that uses a colour palette especially designed for protan and deutan defects. In his work, twenty particular colours that can be well perceived by the protan and deutan defects were designed. And for any input colour image, the protan and deutan confusion colours can be easily replaced by those safe colours. This method is reasonable in some circumstances where only limited colours were included. But for a common colour image, such manipulation will no wonder disrupt the overall image quality. Machado et.al [6] presented an image enhancement algorithm by enlarging the image colour contrast. The key point of their method was to find a lightness-chroma plane that can maximize the contrast loss, which can be simply achieved by adoption of the idea of principle component analysis (PCA). All the colours within an image will firstly be projected to that plane and then rotated to the dichromat's perceptual colour gamut, which was also a lightness-chroma plane but has a different hue angle. Although their method was reasonable when applied to a single image, it did not ensure a consistent colour perception for a particular object appearing in different images. This is to say, one particular colour will be mapped into different colours in different images. In this way, observers can hardly correlate a real object with a particular memory colour.

The motivation for the edge enhancement algorithms is different. It is not aimed for CDOs to discern colours, but to clarify borders between colours. Hence, it is only suitable for some limited applications, like reading maps. A representative example for this kind of algorithm is given by Sakamoto [7]. By confining modifications to such a restricted area, colours in the other regions remain mostly stable.

Pattern superposition [8] is somehow similar to the edge enhancement algorithms. It does not emphasize the discrimination between two confused colours, but add more information beyond colours. Different patterns will be placed on the original image colours, and they can be easily recognized by CDOs. Therefore, this technique is developed to share colour information especially for office documents.

From the above analysis, one can find that most of the algorithms in the literature are applicable only in limited applications. And most of them are specially designed for dichromacies. However, anomalous trichromats can happen at various degrees, ranging from mild, when colour perception is close to the one of colour-normal observers, to severe, when colour perception is similar to the one of dichromats. Hence, the different types of CDOs have different perceived colour gamuts. Algorithms for the dichromacies will, with a strong probability, limit the usages of available colours and impair the colour perceptions of anomalous trichromats. Hence, it is of consequence to investigate their degrees of severity before designing an image enhancement algorithm.

To solve those mentioned problems, a new personalized image enhancement method was proposed. Firstly, the deficiency severity of a CDO will be studied. The corresponding perceived colour gamut can then be established. This is to investigate the range of available colours he can perceive so that we can take the most use of the gamut. Afterwards, the image enhancement problem can be regarded as a gamut mapping problem, *i.e.,* to map colours from the gamut of a CNO to the gamut of a CDO. Hence, a simple gamut mapping algorithm was adopted to ensure a minimized colour shift. The effectiveness of this method was verified by a Psychophysical experiment and present results show that the proposed method is very promising.

Evaluation of severity

As mentioned above, it is necessary to evaluate the deficiency severity for a CDO so that we can estimate the perceived colour gamut. There are plenty of evaluation tools available in the literature, such as FM-100 test [9], D-15 test [10] and anomaloscope test [11].

Since this study is specially designed for applications in display and the final results should be expressed in a quantitative score, a new testing technique, called ZJU50Hue, was developed. This test was adapted from the FM-100 test and was consisting of 50 colours having different hue angles. As shown in Fig. 1, observers were asked to sort these colour patches in a hue order. A misplacement of the colour patch means a confused colour perception. Unlike the original FM-100 test, all the colour patches of the new test were selected from the most up-to-date uniform colour space, i.e., CIECAM16-UCS [12], and were expected to give a more uniform hue perception. In addition, colour patches in a display can be rendered more precisely than the printed ones, resulting in a better experimental setup. More detailed introduction on this method will be reported elsewhere.

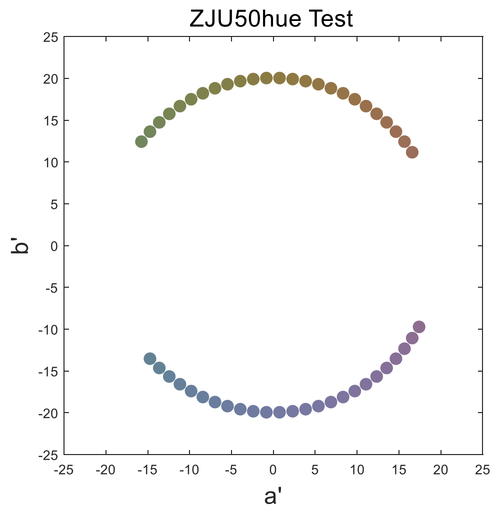

Fig.1.The ZJU50Hue test includes 50 colour patches having different hue angles. It was specially designed for protanomalous and deuteranomalous observers, and only easily confused colours are included.

Results from the colour-vision test were expressed in C-Index [13], which can be regarded as an indicator to reveal the severity of a CDO. The C-index is derived by dividing a subject's major radius by the major radius obtained for a perfect arrangement. A higher C-Index means a more severe colour deficiency and the C-Index for a CNO was unity.

Although the deficiency severity can be well revealed by the C-Index, it cannot be directly utilized to demonstrate the perceived colour gamut of a CDO. To solve this problem, a colour deficiency simulation model [14], specially developed to render colour perceptions of a CDO, was adopted. Inputs of this model include the original image, the type of deficiency and the wavelength shift of the L, M or S cone. Once they were determined, an output image was then achieved, representing the colour perceptions of a CDO. If we change the input wavelength shift from zero to maximum, different degrees of colour vision deficiency, i.e., normal color vision, anomalous trichromacy, and dichromacy can be rendered in a unified way. Hence, the wavelength shift was a good indicator of the severity of colour deficiency. Besides, once the wavelength shift is determined, the simulation model is then ready, which indicates that the perceived colour gamut of a CDO will also be determined.

Relationship between the C-Index and the wavelength shift

To correlate the C-Index with the wavelength shift, a pilot study was performed. In this study, the original ZJU50Hue pattern was sent into the simulation model with varying wavelength shifts, from zero to maximum. CNOs were asked to perform the ZJU50Hue test with those simulated images. Afterwards, their results were analyzed using the C-Index and thus, a relationship between the C-Index and the wavelength shift was finally established. The key assumption behind this experiment is that the CNO's judgements on simulated images correspond to the CDO's judgements on the original images. Hence, the CNOs were used as an evaluation tool to build the relationship between the test result and the wavelength shift.

Seven CNOs participated in the pilot study. Each of them was asked to judge images of various wavelength shifts including 5nm, 10nm, 15nm, 18nm and 20nm. Because protan and deutan are two mostly common types of colour deficiency, a total of 10 tests (= 5 wavelength shifts ×2 types) were included. The whole tests were conducted in a darkened room with all lights turned off. A NEC PA301W display was adopted in this study and was well characterized using a GoG model [15] with an average colour difference less than a CIELAB unit when applied to the Macbeth Colour Checker. The display white was set at D65 @ 100 cd/m2, and the background of the testing interface was fixed at $L^*a^*b^*$ = [50,0,0] to ensure a consistent white adaptation.

The testing results are illustrated in Fig. 2. A red curve and a green curve were included, representing both protan and deutan results, respectively. The small dot represents the testing result for each observer and the big dot represents the average result. An error bar stands for one standard deviation has been added to reflect the scatter of data. A power equation, *i.e.*, $C_{index} = a \cdot ws^b + c$ was adopted to fit the average results. As is shown, the curve is flat at first and ascends quickly. One can notice that the deutan always has a larger C-Index than the protan when their wavelength shift is the same, indicating a poorer colour discrimination.

One may also notice the scatter of the results is not negligible. One possible explanation is that, all the CNOs participating in the pilot study were not trained beforehand. Their capabilities in discriminating colours varied largely. Hence, the results are not so stable. Since only 7 CNOs took part in this experiment, more data are preferred to form a more solid result in the further study.

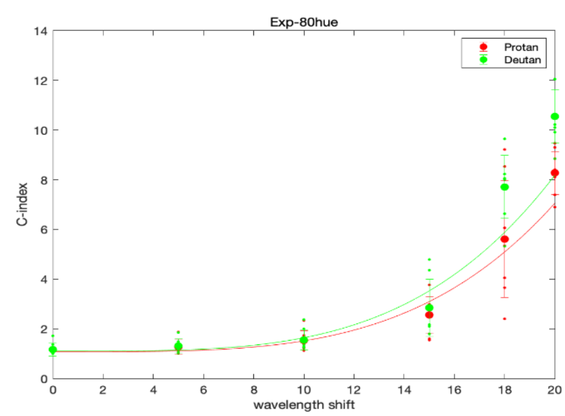

Fig. 2. The conversion relation between C-Index and wavelength shift. The error bar represents a standard deviation.

Perceived colour gamut for a CDO

Once the pilot experiment was completed, a conversion relation was established. CDOs were then asked to perform the original ZJU50Hue test. From their C-Index results, the corresponding wavelength shifts can be easily obtained by referring to the newly built relation.

The wavelength shift of L, M or S cone is of consequence to a CDO and determines the corresponding colour perception. It can be utilized by the simulation model to transform colours from the view of a CNO to the view of a CDO, *i.e.,* the gamut of a CNO can be transformed to the gamut of a CDO by adopting the simulation model developed for the colour vision deficiency. By this means, we can understand how a CDO perceives colours.

The workflow to build the perceived colour gamut for a CDO is given in Fig. 3. Firstly, the input display gamut was densely sampled in the RGB space, which was a 17*17*17 RGB cube in this study. Subsequently, all these RGB values were transformed into the CDO's perceived colour gamut via the simulation model. Afterwards, all the colours expressed in the RGB domain were transformed into the XYZ domain by adoption of the display characterization model, and then the colour appearance attributes. Finally, the gamut boundary descriptors were built by using the segment maxima gamut boundary descriptor algorithm [16].

An example comparison between the gamuts of a CDO and a CNO was given in Fig. 4. This exampled CDO was a protanomaly with a wavelength shift of 10nm. As is shown, they have an obvious gamut difference in most of the hue slices. And the difference is dependent on the hue angle.

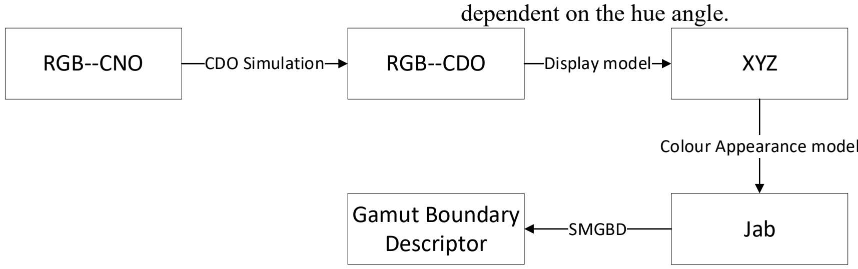

Fig. 3. The workflow to generate the perceived gamut of a CDO.

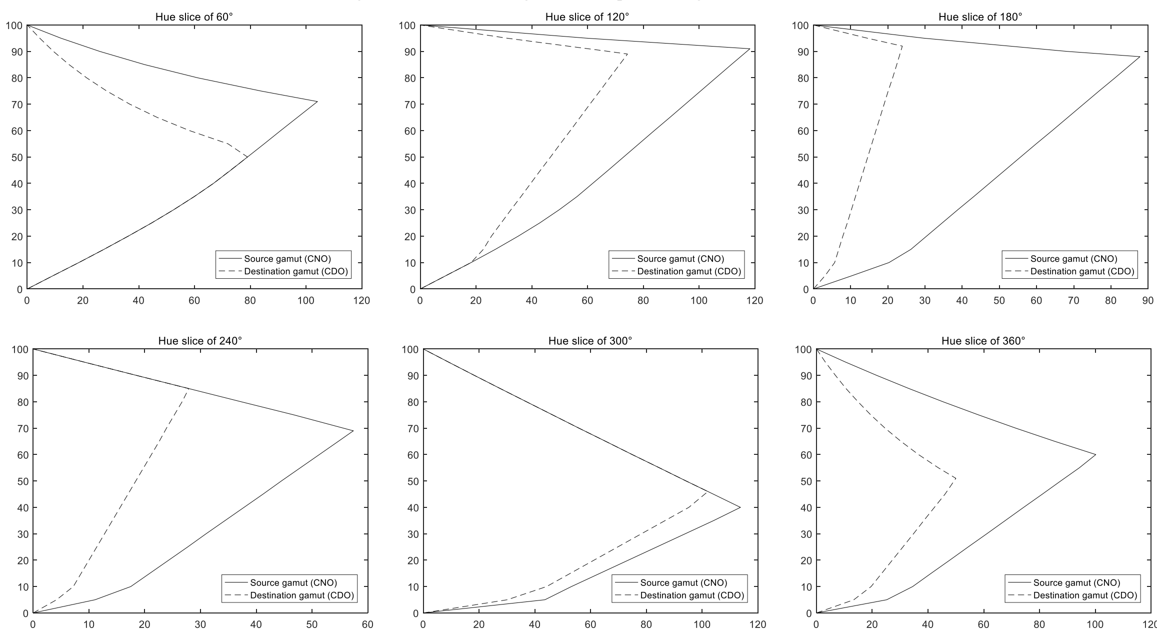

Fig.4. The gamut comparison between CNO and CDO.

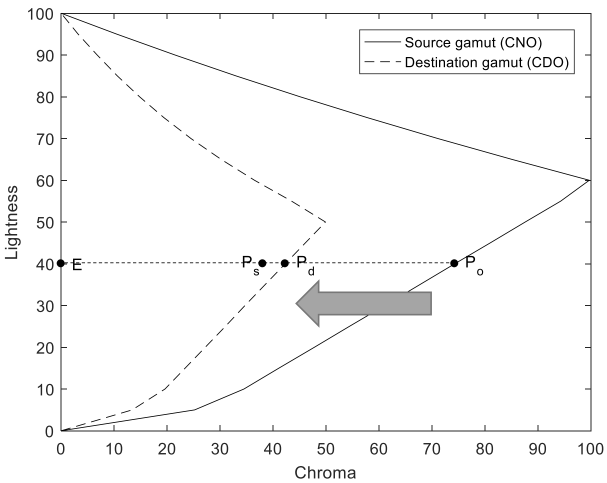

Fig. 5. Mapping towards the lightness axis. P_o is the original colour in the source gamut boundary, and P_d is the mapped colour in the destination gamut boundary. E is the mapping centre on the lightness axis and has the same lightness value as point P_o. The length of EP_s equals to 90% the length of EP_d.

Gamut mapping

As long as the perceived gamut for a CDO is defined, the image enhancement is obtained by performing a gamut mapping between the CNO gamut and the CDO gamut. The gamut compression algorithm adopted in this experiment is simplified from the SGCK [16] algorithm proposed by the CIE.

Fig.5 shows the gamut compression algorithm adopted in this study. A nonlinear knee function was applied to all the source colours. If the source colour was within 90% region of the destination gamut (called the core region), it would be kept unchanged otherwise mapped towards the focal point E, which has the same lightness of the original colour. In other words, the line segment EP_o was mapped to the line segment EP_d and colours in the core region remained the same. This function adopted to perform such mapping is given in Equation (1).

$$\overline{EP'} = \begin{cases} \overline{EP};\ \overline{EP} \le 0.9 * \overline{EP_d} \\ 0.9 * \overline{EP_d} + \dfrac{\overline{EP} - 0.9 * \overline{EP_d}}{\overline{EP_o} - 0.9 * \overline{EP_d}} * \dfrac{\overline{EP_d}}{10};\ \overline{EP} > 0.9 * \overline{EP_d} \end{cases} \quad (1)$$

In Equation (1), E is the focal point; P is the source colour in the original gamut; P' is the mapping output in the destination gamut. This nonlinear lightness mapping is quite similar to the last step of SGCK, which uses a same knee function mentioned here.

After the gamut mapping, all colours were within the destination gamut that a CDO can well perceive. However, this output image is from the view of a CDO and it needed to be converted back to produce a reproduction from the view of a CNO. This can be easily done by inverting the simulation model. Fig 6 shows an example of the enhanced image as well as the original one.

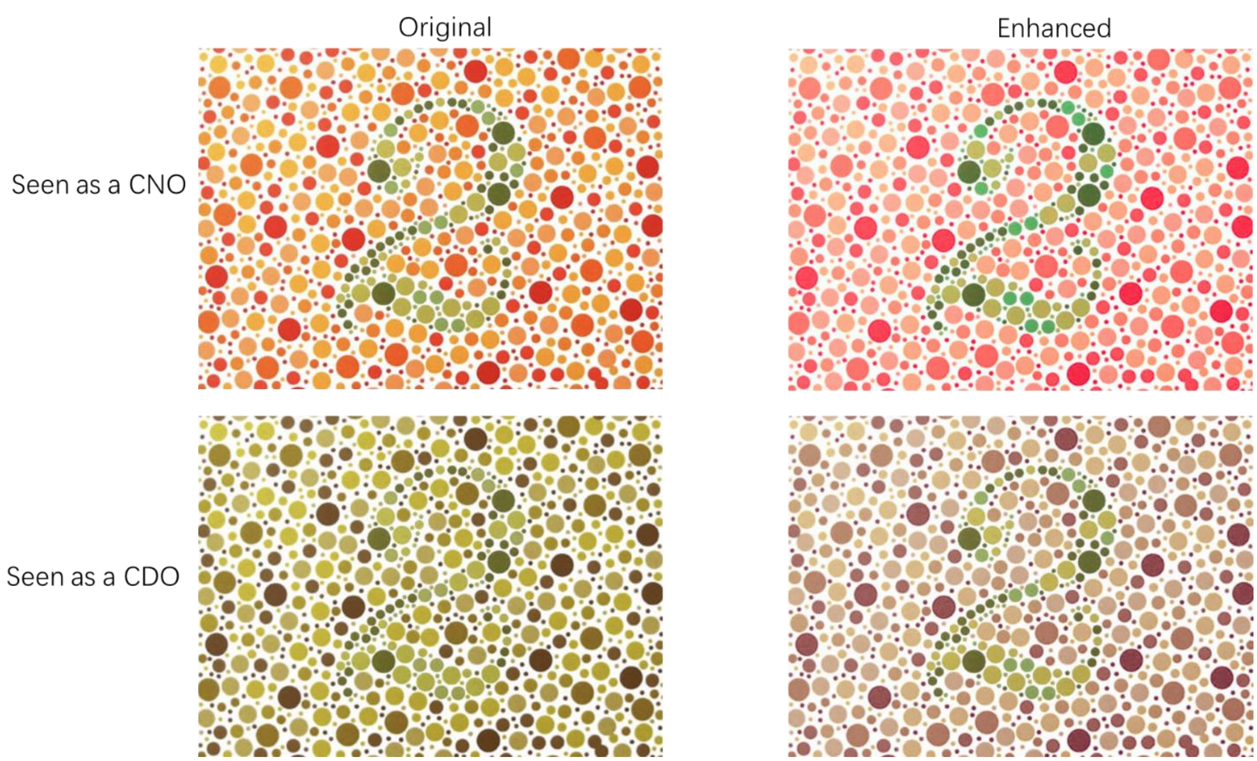

Fig.6. The comparison between the original image and its enhanced one. The wavelength shift is set at 10nm and the CDO is a protanomalous observer.

Validation and discussion

Two Psychophysical experiments were performed to validate the effectiveness of this method. The first one was the same ZJU50Hue test but using enhanced colour patches. When a CDO finished the ZJU50Hue, the wavelength shift was then acquired by referring to the relationship curve developed in the pilot study. Afterwards, the enhanced colour patches were generated by using the gamut mapping algorithm introduced in the above section. The observer was again asked to perform the same task but using the enhanced colour patches. If the proposed method was valid, the colour perception of a CDO will be enhanced, resulting in a better testing result.

Another experiment was based on images. Instead of colour patches, images were more common in our daily life. The CDO was asked to choose a better one between the original image and its enhanced reproduction in terms of colour discrimination. Five images were selected in this experiment, as shown in Fig.7. All of them were carefully selected to contain confusion colours and can be divided into two major groups, i.e., natural images and scientific visualization images. The former group contains images of natural scenes that related to our daily life. The latter group contains images of artificial representations and synthetic colours, mainly developed for scientific visualization or entertainments like computer games.

Five CDOs participated in this experiment and all of them were deuteranomalous observers with severe colour deficiency. The experimental setup was the same as the pilot study. Experimental results were summarized in Table 1. Due to time limitation, the first observer did not take part in the first experiment, so his data was not included. Another issue needs to be clarified is the wavelength shift. After the first two CDOs finished their experiments, they complained that the enhancement was too strong and was beyond their expectation. Hence, for CDO3 to CDO5, their calculated wavelength shifts reduced by 5nm, resulting in a reduced strength of enhancement. This may be due to the inaccuracy of the conversion relation between the C-Index and the wavelength shift as explained in the pilot study. However, it should be noted that, although the wavelength shift was not acquired so precisely, it did not mean the enhancement failed. Images still got enhanced by using the method proposed, but only to a limited extent.

As expected, the C-Index declined significantly when using the enhanced colour patches, indicating the effectiveness of this method. And for most of the testing images, CDOs got better colour discrimination on the enhanced reproductions.

Limitations

Although the proposed method was proven effective to the observers participating in this study, its limitations should also be raised before conducting a large-scale experiment.

This proposed method is based on a colour deficiency simulation model. Its accuracy is influential to the enhancement performance. Besides, a well-designed colour vision test is preferred. A precise evaluation ensures a proper estimation of the severity of a CDO. Both of them contribute to the acquirement of the perceived gamut of a CDO. The gamut mapping algorithm, on the other hand, determines the enhancement strategy. Different gamut mapping algorithms are based on different assumptions, and we need to pick a suitable one according the gamut differences between CNO and CDOs. Another thing should be mentioned is that, the perceived colour gamut is largely influenced by the deficiency severity for a CDO, and colours outside the gamut will be severely compressed. And as is shown in Figure 6, the enhanced image will exhibit somehow chromatic, indicating it is less natural for the CNOs.

In the pilot study, the conversion relation derived was not so consistent among CNOs. This may be attributed to their different capabilities in discriminating colours and can be well re-solved by pre-trainings.

In the validation experiment, all the participants were deuteranomalous observers with sever colour deficiency. More CDOs are needed to fully evaluate the performance of this method, including observers with mild to server colour deficiency.

Conclusion

This paper proposed an effective image enhancement method to improve the colour discrimination for colour vision deficiency observers. It includes 3 stages:1) the establishment of the conversion relation between colour vision test results and the wavelength shift, 2) the acquirement of the perceived gamuts of CDOs, and 3) the gamut mapping between CNOs and CDOs. The present psychophysical experiments show quite promising results. And more experiments are required to further verify this method.

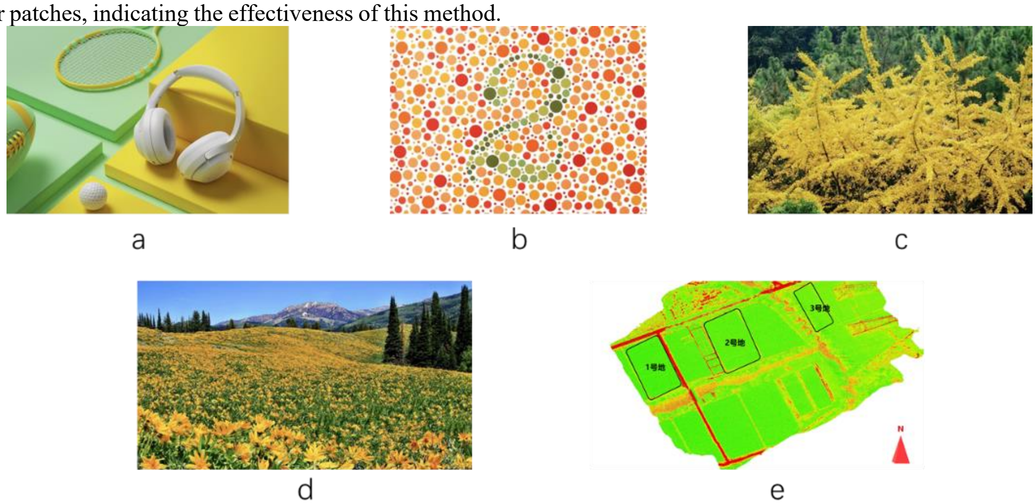

Fig. 7. The testing images for the validation experiment.

Table 1. The testing results for the psychophysical experiment. The wavelength shift in brackets was obtained from the correlation curve. A check mark means the CDO prefers the enhanced reproduction.

	CDO1	CDO2	CDO3	CDO4	CDO5
Wavelength Shift	17nm	12nm	15nm(20nm)	10nm(15nm)	10nm(15nm)
C-Index	/	23%↓	50%↓	38%↓	89%↓
Image a	√	√	√	√	√
Image b	√	√	√		√
Image c		√	√		√
Image d		√	√	√	
Image e		√	√	√	√
Portion of enhanced	40%	100%	100%	60%	80%

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