Effect of spatial structure on colorfulness adaptation for natural images

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We examined whether the perception of the colorfulness of an image is influenced by the adaptation of the visual system to natural and shuffled images with different degrees of saturation. In the experiment, observers first became adapted to several images with different levels of saturation and then their colorfulness perception of a test image was measured. The results show that their perception of colorfulness was influenced by their adaptation to the saturation of images. The effect was stronger following adaptation to natural images than to images consisting of a shuffled collage of randomized color blocks, which suggests that the naturalness of the spatial structure of an image affects the strength of the effect. © 2012 Optical Society of America

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1. INTRODUCTION

Although color distribution in different natural environments is highly variable, visual systems are able to adapt to two major dimensions of color in these environments, namely brightness (dark and light adaptation) and the hue of light (chromatic adaptation), both of which have been the subject of much study. The third dimension of color, however, namely, saturation, has received less attention. Previously, it has been shown that the visual system can selectively adapt to one axis of chromatic modulation; this adaptation is known as "color contrast adaptation" [1–7]. There is also a simultaneous effect in which color appearance depends on the surrounding chromatic variance, which is known as the "gamut expansion effect" [8–10]. These reports suggest that adaptation can have an effect on the perceived saturation and contribution of higher order mechanisms in the visual system. These studies, however, used relatively small, simple patterns on a display. Hence, it is still not well understood how much these color adaptation effects influence our perception of real environments or natural images [4] and what types of visual mechanisms contribute to our response.

In the field of image science, on the other hand, displays with a wide dynamic range are currently being developed, but further work is still needed to expand the color gamut in order to present the wide range of colors that are encountered in natural environments. The evaluation of image quality will be especially important for such displays. It has been shown that the saturation of images plays an important role in perceived image quality [11–13]. However, when a visual system adapts to a certain range of color distribution, the appearance of this range may be altered. Following the adaptation to a wide color distribution, a saturated image may be perceived as being desaturated, or vice versa. Hence, it is important to know how the impression of colorfulness changes following the adaptation to different levels of saturations.

We have previously investigated whether adaptation to the changes in saturation shifts the perceived saturation or colorfulness of complex natural images [14]. We tested how the perceived colorfulness of a test image was altered following the adaptation to several images with different color gamuts. Images of natural scenes or objects as well as images of a Mondrian pattern (i.e., a collection of color patches) were used for adaptation in order to ascertain if the adaptation effect was determined simply by the color gamut, or if it was influenced by a more natural context. The results showed a weaker adaptation effect for the Mondrian patterns, which suggests that the effect is not determined by the gamut of images. Our set of Mondrian images had a color gamut and average color similar to those of natural images but did not have the information of a natural scene. This could be interpreted as indicating that Mondrian images are actually a collection of colored papers, hence even if they are saturated, they could be considered natural. On the other hand, natural objects have limitations regarding their possible or natural levels of saturation. We could interpret these results as meaning that a higher order adaptation to obtain a stable and natural appearance of objects or environments takes place actively for natural images that portray "meaningful" scenes, but not for Mondrian images. However, the Mondrian image consisted of just 11–14 color patches, and the color distribution itself was unlike that found in natural images. Therefore, it was still not clear if the adaptation effect was influenced by the color distribution of an image or if the natural contents of an image were an important factor.

In this study, we investigate whether the naturalness of spatial structure influences the strength of the colorfulness-adaptation effect. Two sets of images were used for adaptation. The first set included images of natural scenes or objects (the same as in our previous research), and the second set included images consisting of a shuffled collage of randomized color blocks cut from the original image. The aim was to determine whether the adaptation effect was a result of the color distributions or of the natural content of the image. If the colorfulness adaptation was due to a change in sensitivity in the relatively low levels of the visual system, the results for both image sets would be expected to be similar, because they have the same color characteristics. If a higher order adaptation was required to obtain a stable and natural appearance of objects or environments, the adaptation effect would be stronger for natural images.

In Experiment 1, the adaptation effects obtained using natural images as adaptation stimuli were compared with those obtained using the set of shuffled images. In Experiment 2, tests were conducted using shuffled images with different block sizes in order to examine the influence of the recognition of scenes and images. In Experiment 3, a single image (natural/shuffled) was used for both the adaptation and test stimuli in order to ascertain if the adaptation effect is stronger when the adaptation and test images share similar color and spatial characteristics or if it is stronger when the images have a natural spatial structure.

2. EXPERIMENT 1

A. Images and Image Modulation Methods

All images were adopted from existing color image data sets: Standard High Precision Picture (SHIPP) data provided by the Institute of Image Electronics Engineering of Japan (IIEEJ), and ISO/JIS-SCID (graphic technology—prepress digital data exchange—standard color image data). As shown in Fig. 1(a), six images were used to prepare the adaptation images. They were chosen in order to present a variety of indoor and outdoor scenes so that there would be no bias in the specific characteristics of the images. The resolution of the images was 500 × 400 (or 400 × 500) pixels. Each image had a different distribution of metric chroma and average color, but we did not modify these characteristics so as to maintain the natural color appearance of the each image and to avoid adaptation to a particular chroma.

Shuffled images were also used in order to test if the color distribution was critical for adaptation or if adaptation was more sensitive to natural features, such as recognizable objects and the naturalness of the spatial structure in an image. As shown in Fig. 1(b), six images were created from the corresponding original natural images in Fig. 1(a) by cutting the original image into 20 × 20 blocks and arranging them randomly. Therefore, the shuffled images had a color distribution similar to that of the natural images, but had spatial characteristics that were different from those of natural scenes.

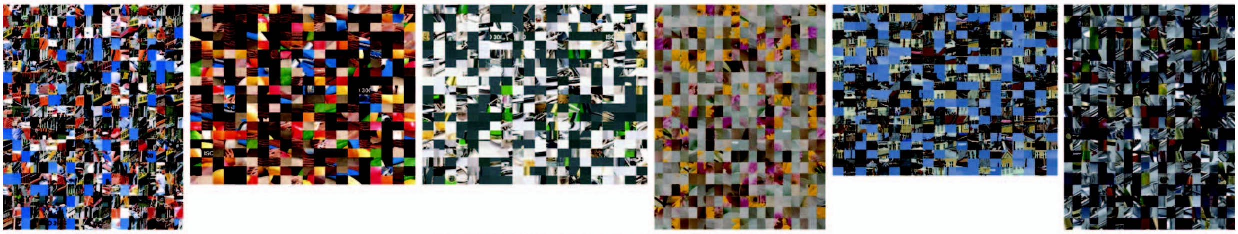
The image "wool" was used as a test image for the evaluation of colorfulness, as shown in Fig. 1(c). This image was not included in the adaptation images and was used for both the natural and shuffled image adaptation conditions.

Table 1 shows the average metric chroma C^* of each image used in the experiments. The fourth column indicates the original C^* of each image. The modulation of images was performed in the CIELAB space, and the metric chroma C^* defined by Equation (1) was used as the parameter of saturation:

$$C^*{}_{ab} = \sqrt{a^{*2} + b^{*2}}. \qquad (1)$$

The metric chroma of the images was modified by multiplying a modulation coefficient k (Eq. 2) while the lightness of the images was kept the same:

(a) Natural Image set (Original)



(b) Shuffled Image set (20×20)

(c) Test Image

Fig. 1. Adaptation and test images: (a) natural image set (original), (b) shuffled image set (20 × 20), (c) test image "wool" with modulation coefficient $k = 0.3$ (left); 1.0 (original, center); and 1.3 (right).

Table 1. Examples of Average Metric Chroma of Each Image Used in Experiments

	C^*_{modified} ($C^*_{\text{modified}} - C^*_{\text{original}}$)						
k	0		0.5		1 (original)	1.5	
Image 1	0	(−19.7)	9.9	(−9.8)	19.7	28.3	(8.6)
Image 2	0	(−25.6)	12.8	(−12.8)	25.6	35.7	(10.1)
Image 3	0	(−6.1)	3.1	(−3.0)	6.1	8.9	(2.8)
Image 4	0	(−18.2)	9.1	(−9.1)	18.2	24.2	(6.0)
Image 5	0	(−14.4)	7.2	(−7.2)	14.4	21.5	(7.1)
Image 6	0	(−9.0)	4.5	(−4.5)	9.0	13.2	(4.2)
Adapt image mean	0	(−15.5)	7.8	(−7.7)	15.5	22.0	(6.5)
k			0.3		1 (original)	1.3	
Test image			9.1	(−21.2)	30.3	37.4	(7.1)

$$C^*_{\text{modified}} = kC^*_{\text{original.}} \tag{2}$$

Four adaptation levels—$k = 0, 0.5, 1.0, 1.5$—were tested for each adaptation image. Test images with eight metric chroma levels ranging from $k = 0.3$ to $k = 1.3$ in intervals of 0.1 were prepared for the evaluation. Three images in Fig. 1(c) show the examples of the test images with the modulation coefficients $k = 0.3$, 1.0 (original), and 1.3, respectively. The average C^* values of each image corresponding to each modulation coefficient k are also shown in Table 1.

B. Experimental Conditions

The experiments were conducted in a dark experimental booth. The stimulus images were generated on a VSG 2/5 graphic board (Cambridge Research Systems), controlled by a PC and presented on a 21 in. CRT display (SONY Multiscan G500). The observers each sat with their head on a chinrest 80 cm from the display, and the visual angle of the images was 18.1 × 13.8 (or 13.8 × 18.1) degrees.

C. Procedure

After 3 min of dark adaptation, an observer adapted to a series of images displayed on a black background. The adaptation images appeared for 2 s in random order with no interval for a total of 3 min, and then a test image at one of the eight saturation levels was presented for 3 s. Observers judged whether or not the test image was too colorful (i.e., unnaturally colorful), and responded by pressing one of two corresponding buttons on a keyboard. They were provided with no reference, and their judgments were based on their own internal criteria. Each judgment was recorded each time a test image was presented, after which the next test image was presented following a 6 s readaptation period.

The method of constant stimuli was used to measure the boundary of colorfulness. Five judgments were obtained for each saturation level of the test image in one session. Two sessions were conducted for each adaptation condition. A psychometric curve obtained by probit analysis was drawn based on a total of ten judgments. A modulation coefficient at 50% on the curve was considered the boundary between judgments of colorfulness being “natural” versus “too colorful.”

The same procedure was repeated for four adaptation levels—$k = 0, 0.5, 1.0, 1.5$—for the sets of natural and shuffled images. A condition with no image adaptation was also tested as a control. In the control condition, observers adapted to the dark monitor during the adaptation phase and between test images. Four observers, NI, HO, YUM, and YOM, participated, all of whom had normal color vision.

D. Results

Figure 2 shows the results for the four observers. The abscissa indicates the modulation coefficient of the adaptation level, k_a. The ordinate indicates the coefficient of the test image, k_t on the boundary of colorfulness, which is calculated from the psychometric function based on the judgments of colorfulness.

The results show that the boundary of colorfulness increases according to the adaptation level in both the natural (square) and shuffled (triangle) adaptation conditions. This means that the observer’s impression of colorfulness was

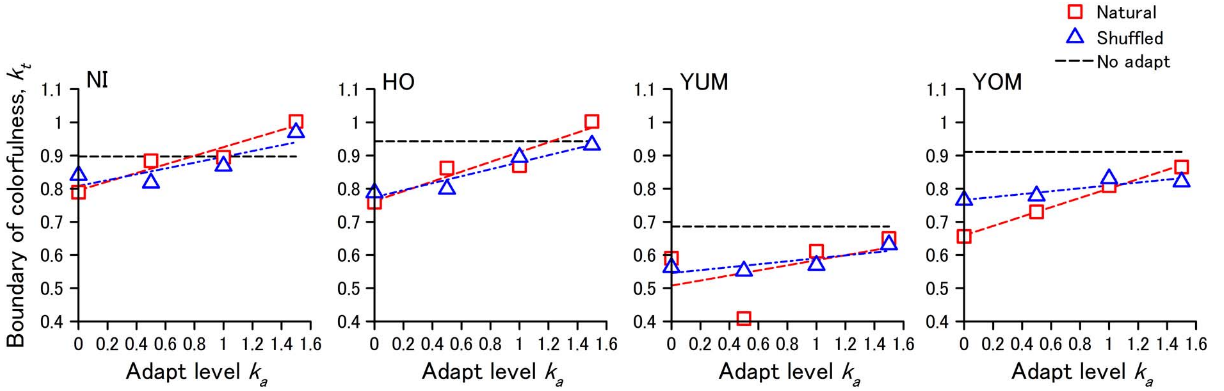


Fig. 2. (Color online) Results for the boundary of colorfulness in Experiment 1, based upon four observers, as shown by the modulation coefficient. The squares and triangles indicate the natural and shuffled images, respectively. The dashed line indicates no-adaptation condition.

influenced by the series of images used for adaptation. Linear fitting lines for the plots of the natural and shuffled images are indicated by the dashed and dashed–dotted lines, respectively. The slopes of the natural image are steeper than those of the shuffled images for all observers, which indicates a larger shift in the boundary, depending on the saturation levels for the natural image condition. The results for YUM yielded data that deviated from those of the other observers, probably because the long period of time between sessions somehow changed this person's internal criteria.

It should be noted that the boundary was close to the original test image with no modulation ($k = 1$) for most observers in the control (no-adaptation) condition, but that it shifted after adaptation to a set of images and thereafter showed large individual differences. The adaptation images were modulated in the direction of both saturation and desaturation, but even at the most saturated level ($k = 1.5$), the mean chroma of the adaptation image ($C^* = 22.0$) was lower than that of the original test image ($C^* = 30.3$). Thus the adaptation effect always shifted in the direction of desaturation for a test image with high chroma. The criterion of the observers was regulated by exposure to a series of images with lower chroma, at least for observers HO, YUM, and YOM.

Because of large individual differences, it is hard to compare the strength of adaptation in each adaptation level. However, the slopes in Fig. 2 can be considered to indicate the strength of the adaptation effect. To compare the effect more clearly, the slope of the fitting line is shown in Fig. 3. All observers showed a larger adaptation effect for natural images. The average for the four observers was 0.12 (SD = 0.016) and 0.070 (0.015) for natural images and shuffled images, respectively. There was a significant difference between the two image sets (paired student's t test, $p = 0.036$).

E. Discussion

Our results show that adaptation to image saturation does cause a shift in the perception of natural images. The effect was different for natural images and shuffled images.

The adaptation images were randomly changed so that the local stimulation of the retina would be continually changed. Adaptation effects were obtained even in such conditions. The order of presentation of the adaptation images was randomized so that the image shown just before a test image was different each time. We also confirmed that the judgments of colorfulness were not based on a simple comparison with the final adaptation image. This means that adaptation does not take place due to a contrast difference in contrast with the previous image, but is in fact a response to a series of images with different color variations. This suggests that the adaptation effect is not due to change in local or low-level sensitivity, but rather to mechanisms that reflect the overall statistical results of the images.

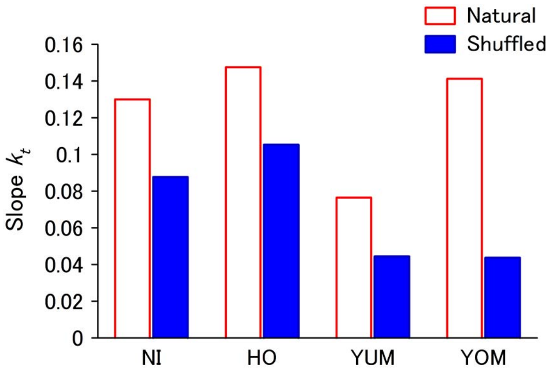


Fig. 3. (Color online) Slope of the boundary of colorfulness in Experiment 1, based upon the results from four observers. The open and filled bars indicate natural and shuffled images, respectively.

The results could be interpreted as indicating that a higher order adaptation for obtaining a stable and natural appearance of objects functions more actively for natural images that portray "meaningful" scenes, than for shuffled images in which the scenes and objects are barely recognizable. This finding is consistent with the previous results obtained using a Mondrian image. It should also be mentioned that the spatial frequency component of the shuffled images was different from that of the natural images due to the edges of the many rectangular pieces, which disrupt the continuity of a color areas within an image. These factors could affect the parvocellular or cortical cell responses in earlier stages of the visual system prior to image recognition, but based on the results in Experiment 1, we cannot tell what this effect might be. These issues are addressed further in Experiment 2 and the General Discussion section (Section 5).

3. EXPERIMENT 2

In Experiment 1, it was shown that the impression of an image was less colorful following exposure to saturated images, and vice versa. This effect was weaker when shuffled images were used for adaptation instead of natural images. This implies that the adaptation effect is stronger for images with a natural spatial structure and with recognizable scenes and objects than it is for shuffled unrecognizable images.

Here, we examine how the effect of adaptation to colorfulness changes depending upon the recognition of images. Different types of image sets were used as adaptation images: natural images and shuffled images with different degrees of segmentation. It was predicted that once it became difficult to recognize a scene and the objects in an image, the colorfulness-adaptation effect would become weak if it depended upon the recognition of images.

A. Experiment

Different types of image sets were used as adaptation images: natural images and shuffled images that consisted of a collage of randomized color blocks cut from the original images with different degrees of segmentation (5 × 5, 10 × 10, and 20 × 20 blocks). An example of this segmentation is shown in Fig. 4. The experimental settings were the same as in Experiment 1.

Two saturation levels, $k = 0.5$ and 1.5, were examined for each image set. The test image and experimental procedure were the same as in Experiment 1.

We also tested the observers' subjective evaluations of the scene and their object recognition for adaptation images in order to confirm the correspondence between the recognizability or the naturalness of images and the degree of segmentation. Observers made their evaluations for each adaptation image, with no modification of the saturation. They did so using a five-scale score, ranging from 1 (image is unrecognizable) to 3 [partly recognizable (each object, etc.)] to 5 (the entire image is recognizable). The evaluations were conducted in a separate session after the observers had completed

Natural 5×5 10×10 20×20

Fig. 4. (Color online) Example of segmentation of adaptation image (Image 2) in Experiment 2.

their testing of all conditions in the colorfulness-adaptation experiment. Images were presented for 10 s each in descending order of segmentation (20 × 20, 10 × 10, 5 × 5 blocks, then the original image) and observers made their judgment for each image. The viewing conditions were the same as in the adaptation experiments.

Four observers—HM, RA, CK, and YOM—participated, all of whom had normal color vision.

B. Results

Figure 5 shows the results. The observers' perception of colorfulness was altered by adaptation to the levels of image saturation in both the natural and shuffled images. Once again, the effect was stronger for adaptation to natural images than it was for adaptation to shuffled images. To compare the shift in the colorfulness boundary, the slope (or the shift) was taken, as shown in Fig. 6. The effect for the different levels of shuffling was different for each observer, and there was no clear trend common to all observers of a weaker effect for the images with smaller blocks. The average for the four observers was 0.17 (SD = 0.016), 0.084 (0.031), 0.018 (0.017), and 0.045 (0.018) for the natural images and for the 5 × 5, 10 × 10, and 20 × 20 shuffled images, respectively. The only significant differences were between the natural image and the 5 × 5, 10 × 10, and 20 × 20 shuffled images (Tukey–Kramer test, $p = 0.049$ for 5 × 5; $p = 0.00082$ for 10 × 10; $p = 0.0042$ for 20 × 20).

Figure 7(a) shows the results of the subjective evaluations. The ratings for object recognition decreased in correspondence with the levels of segmentation. Figure 7(b) shows the correlation between the evaluation and the slope of change in colorfulness, which shows the strength of colorfulness adaptation. The solid line indicates the fitting obtained using simple regression ($R^2 = 0.59$). The results suggest that the colorfulness-adaptation mechanism worked better with natural images that portray fully recognizable scenes and that once an image is shuffled, the effect becomes weaker, even if the objects in the image are partially recognizable (except for observer RA). The strength of adaptation is correlated to the levels of segmentation, at least in the range that we tested.

C. Discussion

The color distribution was kept the same in the natural and shuffled images. In the shuffled images, however, changes were made to the spatial characteristics, such as the spatial frequency and continuity of color edges. Figure 8 shows the differences in the characteristics of spatial frequency in each of the segmentation levels of Image 2. We analyzed the spectra data by converting a RGB image to the CIE X, Y, and Z channels. Because all images showed similar characteristics, only the power spectra of the luminance (Y) channel is shown in Fig. 8(a). The stronger power in the horizontal and the vertical can be seen in the shuffled images. However, as shown by the log–log plots of the horizontal power spectra in (b), the shape and slope of the spectra did not show any systematic changes. The average slopes of six adaptation images were −3.6, −3.6, −3.5, −3.4 in the vertical power spectra, and −2.8, 2.8, −3.0, −3.0 in the horizontal for the natural, 5 × 5, 10 × 10, and 20 × 20 images, respectively. We cannot determine from those data how the differences in the spatial domain influence the adaptation effect. However, a large difference can be seen between the effects obtained for the natural versus shuffled images, while there is no systematic change depending on the segmentation level. This suggests that the change in spatial frequency had little influence upon the observers' responses. If the effect were somehow related to the dependence of parvocellular or

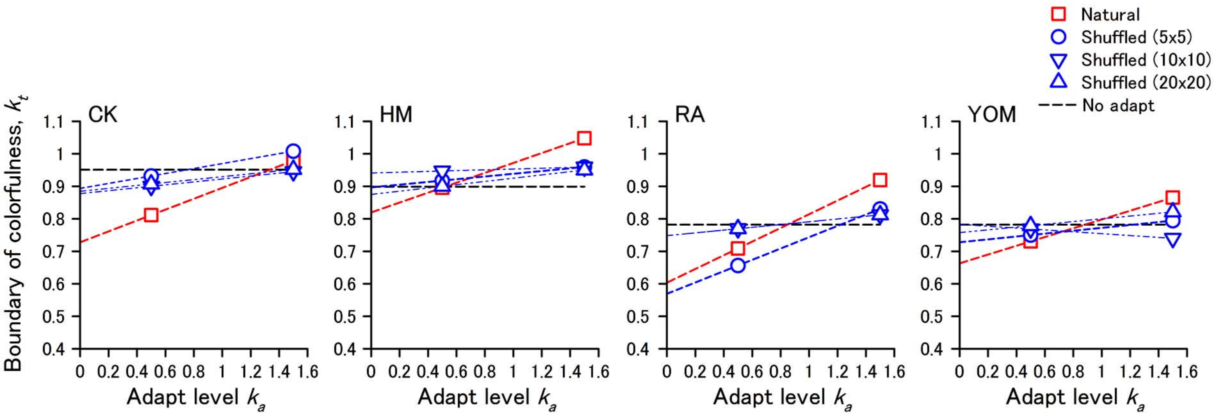


Fig. 5. (Color online) Results for the boundary of colorfulness in Experiment 2, based upon four observers: square, natural image; circle, shuffled image (5 × 5); inverted triangle, shuffled image (10 × 10); triangle, shuffled image (20 × 20). The dashed line indicates the no-adaptation condition.

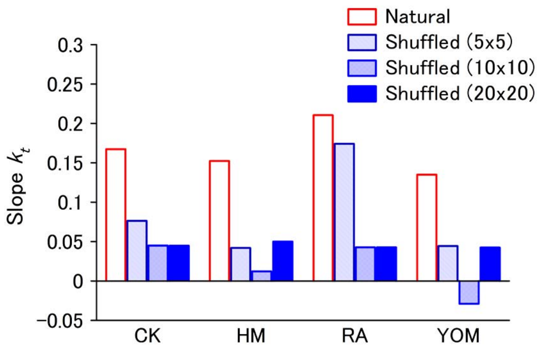


Fig. 6. (Color online) Slope of the boundary of colorfulness in Experiment 2; results are based upon four observers: open bar, natural image; single diagonal lines, shuffled image (5 × 5); criss-crossed diagonal lines, shuffled image (10 × 10); solid bar, shuffled image (20 × 20).

cortical cell responses upon the spatial distribution of color within their receptive fields, the results would be different for the different degrees of segmentation.

4. EXPERIMENT 3

It was shown that the effect of colorfulness adaptation was the strongest for natural images and was weaker for shuffled images, regardless of their level of segmentation. In Experiments 1 and 2, multiple image sets were used for adaptation. These were chosen in order to simulate a normal environment without any intentional control and to avoid any bias in the particular characteristics of images. There was a concern, however, that adaptation to multiple images might make the adaptation effect weaker because of the large variation in the original chroma and in chroma change when modified by multiplying the coefficient k in each adaptation image. Although we changed the overall chroma levels, the shift included a large variance. Furthermore, there were some differences in the degree of recognizability of the scenes in the shuffled images, which could have been responsible for the larger individual differences. In addition, the image “wool,” which was used as a test image for evaluation, was not tested to determine whether the characteristics of a test image influence the adaptation effect. In order to make a direct comparison, in Experiment 3 the same single image was used for both as an adaptation and as a test image, and a comparison was then made of all combinations of natural and shuffled images for both adaptation and the test image. We also examined two different images in addition to “wool.”

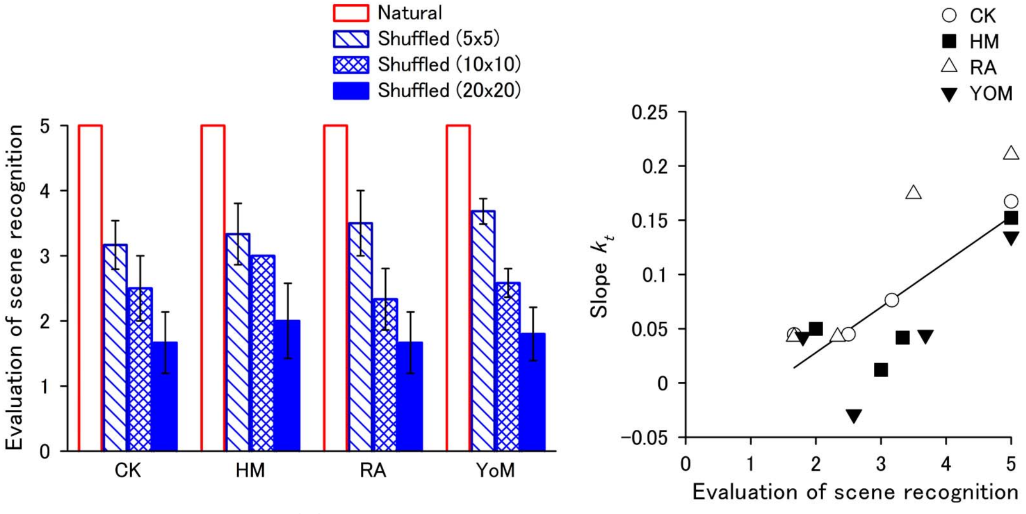
A. Images and Procedure

In addition to the image “wool” used as a test image in the previous experiments, the images “outdoor café” and “harbor” were also used. These images correspond to images 1 and 5 in Fig. 1(a), respectively. We chose images whose characteristics are different from those of the “wool” image, such as an indoor still image with very high chroma. Additional images included outside scenes with metric chroma that are lower than that of “wool,” but high enough to show a recognizable difference in colorfulness when the chroma modification was applied ($C^* = 19.9$ and 14.4).

Two types of images were then compared: a natural image and a shuffled image with 20 × 20 blocks, as shown in Fig. 9. Both were used as adaptation and test images. Two saturation levels, $k = 0.5$ and 1.5, were examined for each adaptation image. Four combinations of an adaptation (natural/shuffled) image and a test (natural/shuffled) image were tested.

The other procedure was the same as in Experiments 1 and 2, except that in the adaptation phase, a single image was shown. Each time it was presented, its position was shifted randomly within 50 pixels to prevent local adaptation and to make it easier to distinguish between the adaptation and test images during the test phase with readaptation. Precisely speaking, this could not guarantee the complete elimination of local adaptation because we did not set a fixation point. However, the observers were instructed to look at the overall monitor and not to follow the image, so that local adaptation was counterbalanced at least some extent.

We confirmed that the observers were also able to make a reliable colorfulness judgment in the case of a shuffled test image in the control experiment. The observers HM, RA,



(a) (b)

Fig. 7. (Color online) (a) Average subjective evaluation of recognizability of scene and object for six adaptation images in Experiment 2. Error bars indicate standard deviation. (b) Correlation between evaluation of recognizability and the colorfulness boundary shown by slope of k_t. The solid line indicates linear fitting.

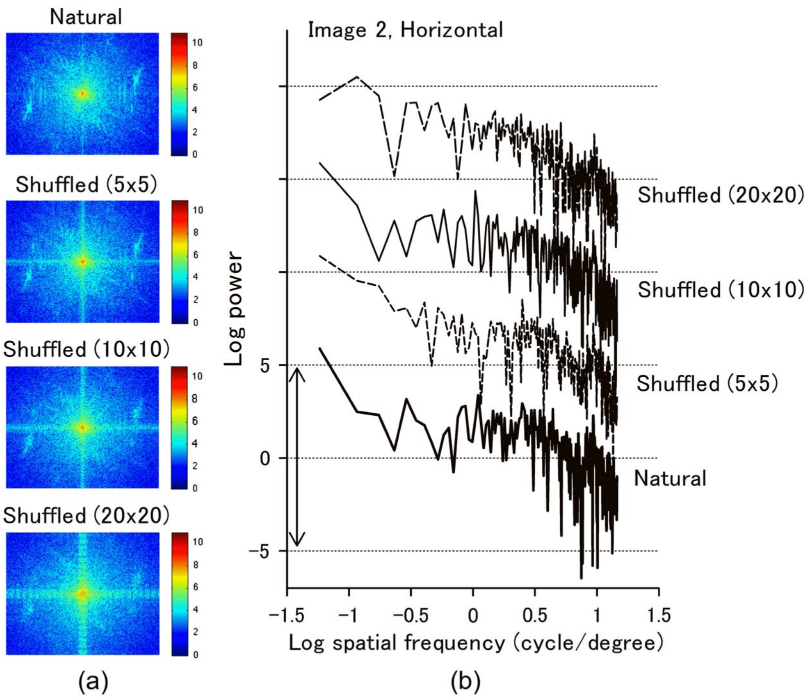


Fig. 8. (Color online) Example of spatial frequency characteristics from Image 2 with different segmentations. (a) Two-dimensional power spectra and (b) horizontal power curves. Note that each spectrum is shifted vertically to allow for easy comparison. The scale is shown on the left of the natural image condition.

CK, and SS responded to the wool image, and SS, TT, and NS to the outdoor café and harbor images. All observers had normal color vision.

B. Results

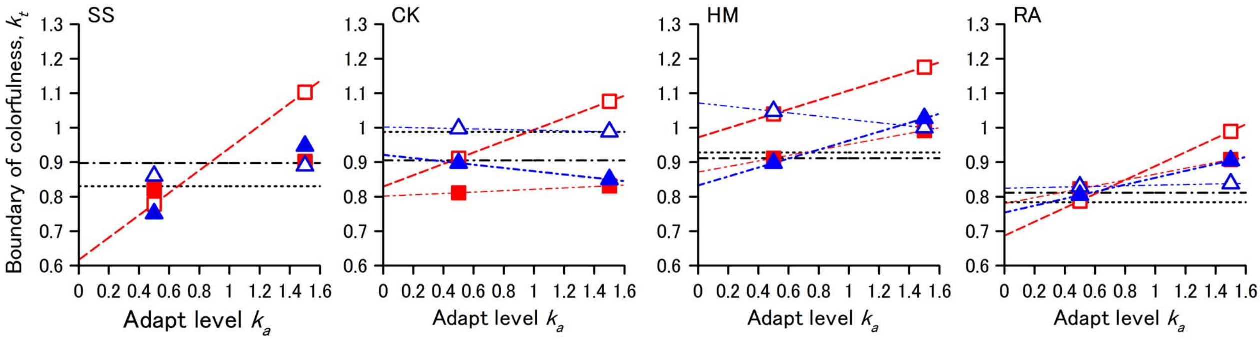
Figure 10 shows the results for wool [Fig. 10(a)], outdoor café [Fig. 10(b)], and harbor [Fig. 10(c)]. Most observers showed some differences in their boundary of colorfulness for the natural and shuffled test images in the control (no-adaptation) condition, as shown by two horizontal lines. The shift, however, was not systematic. In the case of adaptation to the natural image, the slope was much steeper for the natural test image than for the shuffled test image. This indicates that the adaptation effect transfers strongly to a natural test image. In the case of adaptation to a shuffled image, there was no systematic trend regarding the strength of adaptation among the different test images and observers.

To compare the shift in the colorfulness boundary, the slope (or the shift) is shown in Fig. 11. Although there are individual differences, as shown by the error bars, the adaptation effect was strongest for the natural adapt/natural test combination for all observers. As shown in Table 2, simple linear regression analysis confirmed that the slope of the regression line differs significantly from zero only for the natural/natural combination for all images and in the shuffled/natural for "harbor."

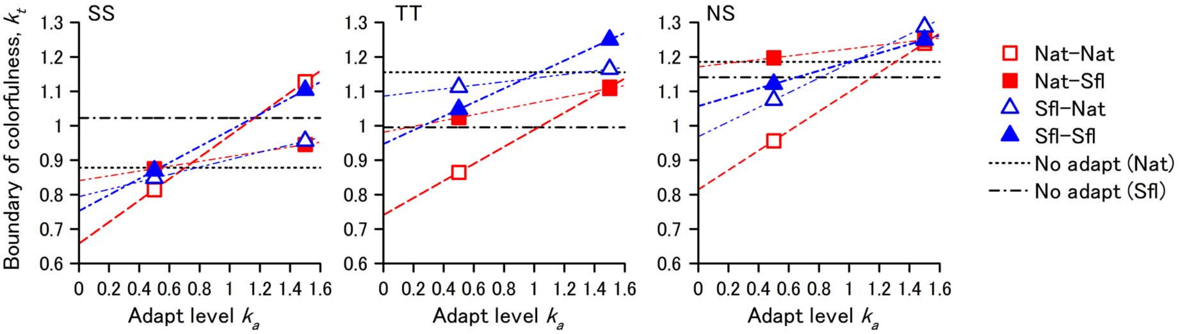
Fig. 9. (Color online) Example of images for adaptation and test ("wool") in Experiment 3.

The average slope of the data of the four observers is also shown in Table 2. For the "wool" image, there was a significant difference between natural/natural and shuffled/natural (Tukey–Kramer test, $p = 0.005$) and a marginally significant difference between natural/natural and natural/shuffled ($p = 0.063$). For the "outdoor café" image, there were significant differences between natural/natural and both natural/shuffled ($p = 0.0047$) and shuffled/natural ($p = 0.025$). For the "harbor" image, there were significant differences between natural/natural and all other conditions ($p < 0.001$), and between shuffled/shuffled and shuffled/natural ($p = 0.031$). The general trends were the same for all three images. There was no significant difference between natural/natural and shuffled/shuffled for "wool" and "outdoor café," even though the data for all observers showed a stronger effect for the natural/natural than for the shuffled/shuffled combination. This is probably due to the small number of observers and the large individual differences.

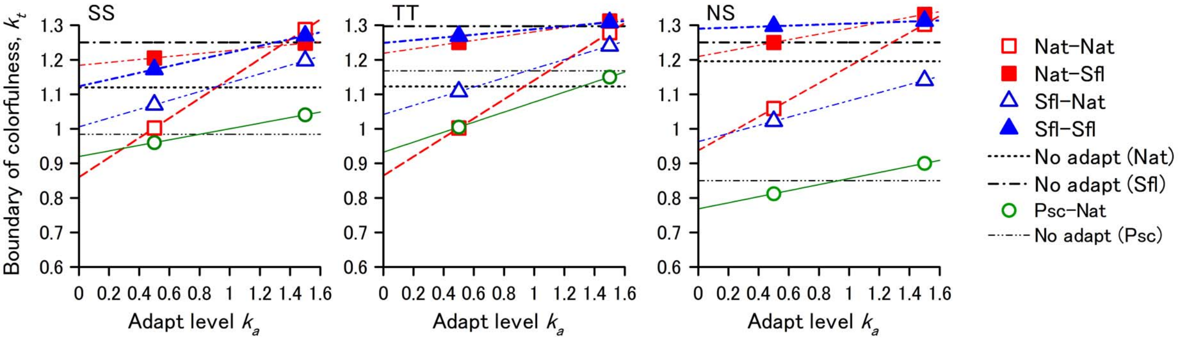
If the strength of the colorfulness adaptation is determined by the similarity between the spatial characteristics of the adaptation and test images, the effect should have been strong in both the natural/natural and shuffled/shuffled combinations. However, the results constantly show a stronger effect for the natural/natural than the shuffled/shuffled combination. This implies that images with a natural spatial structure produce a stronger adaptation effect. The average shift in the colorfulness boundary in Fig. 11 shows that the three images produced a similar trend even though they are different images that were observed by mostly different observers.



(a) Wool



(b) Outdoor cafe



(c) Harbor

Fig. 10. (Color online) Results for the boundary of colorfulness in Experiment 3; based upon four observers: (a) wool, (b) outdoor café, (c) harbor. Open square, natural adapt/natural test; solid square, natural/shuffled; open triangle, shuffled/natural; solid triangle, shuffled/shuffled; open circle, phase-scrambled/natural. The horizontal lines indicate the no-adaptation condition for each test image.

C. Discussion

The trend of colorfulness adaptation was similar for the images "wool," "outdoor café," and "harbor," even though they have different color and spatial characteristics. This suggests that the adaptation effect does not apply for a particular image, but it could be applicable to different images with

Table 2. Statistical Results of Experiment 3—Mean Slope, Standard Deviation, and *p*-Value of Test of Slope for Three Adapt Images

		nat/nat	nat/sfl	sfl/nat	sfl/sfl
Wool	Slope	0.21	0.067	–0.0047	0.095
	SD	0.042	0.016	0.016	0.051
	p	0.029	0.15 (N.S.)	0.95 (N.S.)	0.12 (N.S.)
Outdoor café	slope	0.28	0.069	0.12	0.19
	SD	0.019	0.0094	0.047	0.031
	p	0.0082	0.62 (N.S.)	0.39 (N.S.)	0.10 (N.S.)
Harbor	slope	0.29	0.043	0.13	0.098
	SD	0.28	0.062	0.13	0.040
	p	0.00018	0.10 (N.S.)	0.030	0.28 (N.S.)

different characteristics. We only tested a few images with rather high chroma, so it is possible that the strength of the effect changes depending on the image characteristics. We need to further investigate the strength of the colorfulness-adaptation effect for different natural images.

Although we expected to find a stronger effect and smaller individual differences in Experiment 3, our results did not confirm this expectation. While we cannot explain the reason for large individual differences, this result may show the generality of the colorfulness-adaptation effect in a variety of complex environments.

Interestingly, the shuffled test image showed a generally weaker adaptation for both natural and shuffled adaptation for most observers. This implies that the adaptation effect works between the same types of images with the same spatial characteristics, but it applies more strongly for natural images than for unnatural images. Because sensory changes due to the adaptation effect itself should be the same, regardless of what test image is used, the characteristics of the test image are also important as a means of probing or detecting tendencies.

5. GENERAL DISCUSSION

It was shown that adaptation to image saturation does produce a shift in the perception of natural images. The effect was stronger for natural images than for various types of shuffled images.

We could not eliminate the influence of the change in spatial frequency in the shuffled images from our results, because the analysis of the power spectra in Experiment 2 did not reveal a clear trend in the differences of the shuffled images. We therefore additionally examined a phase-scrambled version of the "harbor" image only for the combination of the phase-scrambled adapt/natural test in Experiment 3. The phase-scrambled images were created using a method similar to that of Yoonessi and Kingdom 18, except that the image was converted to the CIE X, Y, Z channels, and phase-scrambling was applied only to the Y (luminance) channel in order to maintain the same distribution of chromaticity. The results showed a weak adaptation effect for the phase-scrambled adapt/natural test as shown in Figs. 10 and 11. Although we tested under a limited number of conditions, the results suggest that the difference between the colorfulness adaptation for natural and shuffled images was not due to side effects caused by changes in the spatial frequency component.

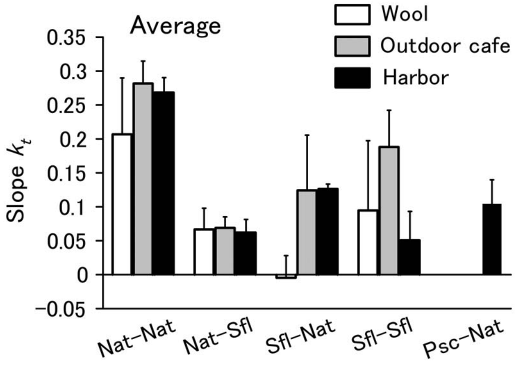


Fig. 11. Average slope of the boundary of colorfulness in each condition: natural adapt/natural test, natural/shuffled, shuffled/natural, and shuffled/shuffled (and phase-scrambled/natural condition for harbor) in Experiment 3. Open bar, wool; dark shaded bar, outdoor café; solid, harbor. Error bars indicate standard deviation.

It is known that higher order mechanisms contribute to many aspects of color vision, such as color sensitivity, color adaptation, and color constancy [15–23]. Similar mechanisms may be responsible for colorfulness adaptation. If such adaptation were due to a change in sensitivity at lower levels, then the effect in natural images would be the same as in simple patterns as long as they have the same color distribution. If, on the other hand, such adaptation takes place at higher cortical levels, the effect could be different, depending on the spatial characteristics of the images. There would be differences in the adaptation effect for natural versus shuffled images because colorfulness adaptation is affected not only by color distributions, but also by higher order spatial characteristics. The colorfulness-adaptation effect is predictable from the color contrast adaptation phenomena [1–5]. However, the difference between the responses to natural and shuffled images cannot be explained only by contrast adaptation, because the color distribution of the images and the local contrast were kept the same.

Yoonessi and Kingdom 18 reported that sensitivity to color changes is higher for natural images than for phase-scrambled scenes. Based on their findings, it may be possible to predict that the lowered sensitivity to chromatic differences that is caused by the reduced "naturalness" of a shuffled image would elevate the threshold for the evaluation of the natural versus unnatural colorfulness boundary. Our results (Figs. 2,5,10), however, did not show that any systematic elevation in the threshold was caused by the introduction of image degradation. This suggests that the difference between the natural and shuffled adaptation image would not affect the perception of the colorfulness of the test images. On the other hand, the boundaries in the control condition of Experiment 3 showed differences between the natural and shuffled test images (Fig. 10), which suggests that the perception of colorfulness itself changes in response to image degradation. The direction and the amount of the change, however, did not show any systematic trends that could be predicted by the changes in sensitivity. Nevertheless, it is interesting to note that our results are consistent with those of Yoonessi and Kingdom 18 in that they show differences in the response to natural and unnatural images, even though the purpose of the study and the method of image degradation are different. This implies that the naturalness of an image affects various aspects of human color perception and recognition.

Furthermore, whether or not adaptation plays a more active role in maintaining a stable appearance within an environment would depend on whether an image includes a natural scene and objects. It is possible that the contribution made by the recognition of a natural context in images is involved. It has also been shown that the degree of color constancy decreases if a photograph is shuffled [24]. This suggests that the recognition of spatial structure is important for the appearance of stable color, because we cannot identify the color of an object under different kinds of illumination, without knowing the spatial context of the object and how the space is illuminated [25,26]. The same would be true for the dimension of colorfulness.

It is also not possible to distinguish whether the main factor that determines differences between the perception of natural and shuffled images is difference in a perceptual sensitivity, or whether it is due to different cognitive judgments based on familiar objects in the images. Further investigation is needed in order to make clear what factor and what levels of processing within the visual system are related to colorfulness-adaptation effects.

Although it was predicted that adaptation to multiple images might weaken these effects, it seems that the individual differences is larger than the differences in the images. We showed that the natural and shuffled images produced clear differences in the effect, and that this trend is not image dependent. However, the variations in both the interindividual difference and interimage difference has not yet been examined well enough. There are probably many factors that affect the strength of the effect in response to a test image or adaptation images, such as color and spatial characteristics, contents, and the method of color modification (e.g., overall versus biased modification). More detailed investigation is needed in this regard as well.

In any case, colorfulness adaptation does takes place with natural images, which implies that in our daily life, we are continually recalibrating our perceptions. This may be a reasonable conclusion if we consider the functional meaning of adaptation. We adapt to an environment in order to maintain a stable appearance of objects, and we therefore need to compensate for overall changes in a natural scene, and we apply that status to the next natural scene we encounter. A collage of color patches, such as that in shuffled images, however, is more of an object plane than a “scene,” so we may therefore prefer to maintain its appearance as is. It would be interesting to consider what factors we actually do need to adapt to. It may not be just a change in color distribution, but could also be a significant change in color distribution, i.e., the variations that commonly occur in natural scenes, such as illumination, fog, and vegetation.

As was mentioned earlier, in the display and printing industries, the gamut of image representation is an important consideration. Our results imply that our impression of images changes by adapting to the color gamut to which we are exposed. Our evaluation of image quality is often based on colorimetric measurements, or on a direct comparison of displays placed side by side. The method of evaluation should be carefully chosen depending on its purpose.

Although further investigation is needed to clarify the characteristics of colorfulness adaptation and its underlying mechanisms, this study has shown that the colorfulness-adaptation effect is stronger for natural images with natural spatial characteristics than it is for unnatural shuffled images. This suggests that spatial structure plays an important role in colorfulness adaptation in response to natural images.

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