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Color Asymmetry in 3D Imaging: Influence on the Viewing Experience

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Abstract Because the chain of events in 3D imaging is vulnerable to different context- and technology-specific variables, it is important to understand the extent to which users can accept feature-specific differences between scenes without a decrease in the (observed) image quality. Twenty participants were asked to view natural stereoscopic still images and evaluate how different combinations of color asymmetries affect the overall viewing experience, the naturalness of the image and the depth perception. As expected, an increase in color asymmetry between the viewer's left-eye and right-eye images decreased the image quality evaluation scores. Certain color-channel-specific changes, such as a decrease in blue values, were more acceptable than others, and some content-specific features, such as a brownish or greenish background, were less sensitive to changes compared to close-up images with brighter objects and backgrounds.

Keywords color asymmetry, stereoscopic content, viewing experience, naturalness, depth perception

1. Introduction

In stereopsis, different levels of visual signal processing are used to search the corresponding points of the retinal images in the left and right eyes to produce depth perception[1, 2]. Depending on the viewer's visual system functionality, stimulus variables, and internal and external stressors, the perception of depth may vary with speed, strength and constancy between viewers and even within a single viewer's experience[1, 2].The same basic principles of stereopsis are often exploited in the production of synthetic stereoscopic content. However, in contrast with natural viewing situations, the differences between the left- and right-eye views may vary extensively and cannot be always controlled. These differences may then affect the perceived depth and other image-quality-related parameters as well as viewing comfort[3-7]. Because the human visual system is dynamic and adaptable to different viewing conditions, it is important to understand to what extent feature asymmetries can be tolerated by viewers without a noticeable decrease in (observed) image quality or viewing experience[8, 9].

1.1. Perception of color

It is well known that human perception of color depends on the observed object's surface properties and the viewing conditions[10-13]. Despite changes in the surrounding illumination, the visual system often recognizes colors as belonging to the same category even though the attributes of color sensation (i.e., hue, brightness, and colorfulness) may vary[10, 14-17]. The results from color constancy studies have shown that when people view images of the same scene under different illumination conditions for each eye, the integration of the color scenes is an easy task. The scene is combined in a way that corresponds to typical binocular viewing, and the evaluated illumination is estimated to lie between the two lighting conditions[14]. According to Yang et al.[11], at least two illuminant cues are active in human color

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vision, a specularity cue and a uniform background cue. However, based on their own and previously published results, the authors suggested that it is likely that more than one cue determines the constancy of color vision, and the importance of the cues varies from context to context[10, 12, 18, 19]. Yang and Shevell[20] studied the effect of binocular disparity on color constancy and found that added binocular disparity improves color constancy in a manner similar to what is experienced with specular reflections. On the basis of these results, the authors concluded that the visual system uses binocular color-related information in addition to other cues in surface color perception. Den Ouden et al.[21] showed that chromatic features also improve binocular fusion, which can be seen as an increase in perceived depth. Additionally, Simmons and Kingdom[22] found that the encoding of disparity information involves the interaction of both luminance contrast and chromatic-sensitive stereopsis mechanisms[23].

Because the perception of colors depends on several factors connected to viewing conditions and surface attributes, different models of the human color vision operating principles (i.e., color appearance) have been presented. Most of these models include stages of chromatic adaptation in which the cones adjust to changes in illumination and respond to different wavelength (L/long-wave channel, M/medium-wave channel, and S-short wave channel) stages in which signals decompose into different channels and finally coalesce in the evaluation stages of perceptional attributes such as lightness, hue and colorfulness[24, 25]. Although the different models explain color perception and appearance from slightly different viewpoints, these models are useful links between the color appearance and color matching processes used in rendering and quality corrections. In particular, the additive primary colors of Red, Green, and Blue (RGB) or CIE tri-stimulus values (XYZ) are often used to describe the color mixtures used in graphics and their connections to the color appearance perceived by viewers[24-27].

In addition to the properties of surface spectral reflectance and illuminants, previous information regarding different colors (i.e., color memory and their connections to the objects in specific contexts) has an important role in color constancy processing[10, 28, 29], object recognition[30], and subjective preferences of image quality[29, 31, 32]. It has been shown that color information improves the recognition of natural objects and artifacts as well as the recognition of photographs and line drawings[30, 33]. According to Guibal and Dresp[34], colors may enhance depth perception, but the outcome also depends on the luminance contrast and stimulus geometry parameters.

1.2. Influence of scene colors and depth on image quality and subjective opinions

The interaction of technological variables, image and image quality models, physical image parameters, and visual algorithms affect and define the perceived quality of a scene (the image quality concept is often used to describe the degree of image excellence, references[35, 36]). In many cases, such as in digital photography and cinematography, an important goal is to generate images that correspond to the real-life scenes[8, 27, 37]. Among other features, changes in scene colors and stereoscopic depth attributes have been shown to affect not only image quality but also image naturalness (how well the colors of the images or added disparity information corresponds to the real-life scenes)[38-40]. For example, Ridder and colleagues[38] studied how the chroma and hue variation in color images of natural content affect the perceived image quality and naturalness. The authors found that both the image quality and naturalness decreased when the hues began to deviate from the original images, whereas the influence of chroma changes was weaker and more varied; the participants preferred more colorful images that were not always the most natural ones. The research results presented by Yendrikhovskij et al.[31] showed that judgments of naturalness vary between different content-related categories, but that participants seem to be more consistent in naturalness judgments of typical categories such as skin, grass, and sky than with categories that also vary in the real-life situations (see also references[41, 42]). Moreover, based on correlations between the naturalness judgments of the salient image object (skin) and the entire picture, the authors suggested that the most critical object in a scene might determine the naturalness of the picture as a whole. According to Guan and Hung[43], at least six different psychological factors (i.e., color memory, comfort, harmony, colorfulness, color performance of the area of interest in the image, and color-related positive associations) can be used when the image color preferences are evaluated, but the relative importance of these factors varies depending on the nature of the content.

Similar to the image color attributes, the added disparity information could make the experience more realistic by increasing the naturalness of the image[40, 44, 45]. According to the view of Lambooij and colleagues[44] (see also reference[46]), the naturalness and the viewing experience are both important attributes when the effect of binocular disparity information on specific content is evaluated. However, because naturalness takes into account both the added value of stereoscopic depth and the image quality and is more sensitive to variations in screen disparity, it is a more appropriate concept for evaluating the added value of disparity information than measuring the viewing experience.

In addition to the naturalness and viewing experience, added stereoscopic depth interacts with other image quality attributes[44, 45, 47]. Pölönen et al.[45] showed that the depth perception remained relatively unchanged when the luminance and illuminance levels of the display were varied. The only clear decrease in depth levels was found when a low luminance of 9.73 cd/m^2 was used in office and outdoor illuminance. Lambooji et al.[44] in turn found that added blur, noise, or screen disparity may affect both image quality and perceived depth, and blur or noise could decrease image quality and depth perception, whereas added disparity may increase perceived depth but can also decrease image quality. Kuijsters et al.[40] studied the effect of chroma variations on the naturalness and image quality of stereoscopic images. The results showed that participants seem to use similar approaches when evaluating the image quality and naturalness of color manipulations of 2D and stereoscopic 3D images. A small increase in chroma was found to affect image quality but not naturalness, whereas a parallel increase in depth and chroma levels helped to distinguish among different depth layers.

1.3. Colors in stereoscopic images and video processing

It is well known that when people use binocular (stereoscopic; different images in left and right eye) or bi-ocular wearable near-eye displays (same image in both eyes), different asymmetries between the image parameters and the optical characteristics of the displays may cause viewing discomfort and decrease the image quality of the content[3-6]. Similar to the wearable displays, stereoscopic camera systems may exhibit problems with camera sensors and optics alignment and even in system design as a whole. In addition, these devices are also sensitive to variations in lighting conditions, which may cause discrepancies between the left- and the right-eye images (e.g., in chroma and luminance) and thus affect image-quality-related attributes[7].

Many of the color rendering algorithms are based on specific assumptions, and when these assumptions are not realized, the reproduction or correction of color may fail [48, 49]. Recently, new algorithms for color rendering have been presented and have been shown to improve color constancy performance and image quality in natural scenes [49, 50]. For example, instead of estimating the illuminance of the scene, Siddiqui and Bouman's[50] hierarchical color correction algorithm classifies images into different groups based on global and local classification of the image color attributes, such as predominantly reddish, bluish, yellowish/greenish, bluish or with no dominant color-cast. Gijsenij and Gevers[49] showed that image color constancy could be improved when selection of different algorithms is used, and the selection is made on the basis of image attributes known to have an effect on color constancy.

An algorithm used for stereoscopic image rendering often looks for specific similarities between the views[7]. Because of this, different color attributes in scenes could be used for stereo matching[7, 51], among other factors. However, if certain types of discrepancies exist between the color attributes in the views, the use of color similarities may actually decrease the perceived image quality and other qualities[52]. Lately, different approaches based on asymmetric rendering of single views have been presented [8, 9]. Such modifications are based on the assumption that the less dominant view will be suppressed by the dominant one [53, 54]. For example, Bulbul et al.[9] tested different graphics rendering and modeling methods for stereoscopic still images and found that a single view modification was not perceptible when it decreased the intensity contrast. Aflaki and colleagues[8] studied the influence of an asymmetric stereoscopic video coding technique based on an uneven quantization step-size for luma sample values of different views. The results showed that the use of different sequence quality did not affect the viewing experience, and compared with other coding techniques, the image quality of the asymmetric codec was superior.

In summary, asymmetric corrections of color and the use of color matching in stereoscopic rendering can improve the viewing experience, image quality, and naturalness. However, because integration of scenes with color differences is a relatively easy task for humans, and the resulting colors are evaluated on the basis of an average illuminant, some of the color changes do not necessarily affect the viewing experience. The primary goal of the present study was to investigate how different changes in specific color mixtures affect the overall viewing experience (including image quality), naturalness, and depth perception when stereoscopic natural scenes were viewed. In addition, the influence of selected content-specific features was examined.

2. Method

2.1. Equipment

To avoid the influence of crosstalk on the viewing comfort, image quality, and depth perception, a fixed mirror stereoscope system was used to create stereoscopic images [55]. Stimuli were displayed on a 22.2" ViewSonic VP2290b display (204 ppi) on a gray background. The display was viewed through the stereoscope, and optical properties for the display were determined by measuring grey levels with a spectroradiometer (PhotoResearch SpectraScan PR-670) through the stereoscope at a 40-cm viewing distance. The obtained luminance values for grey levels 255 (white) and 0 (black) were 126.6 cd/m2 and 0.4 cd/m2, respectively.

2.2. Procedure

Each test session began with a visual screening (visual acuity, near and far visual acuity, stereo acuity, color vision, near horizontal phoria, and the near point of accommodation), after which participants completed a questionnaire containing background questions (e.g., name, gender, age, 3D experience, vulnerability to motion sickness/headache, interest in new technology) (Fig. 1). In the next step, participants were introduced to the task and started the test.

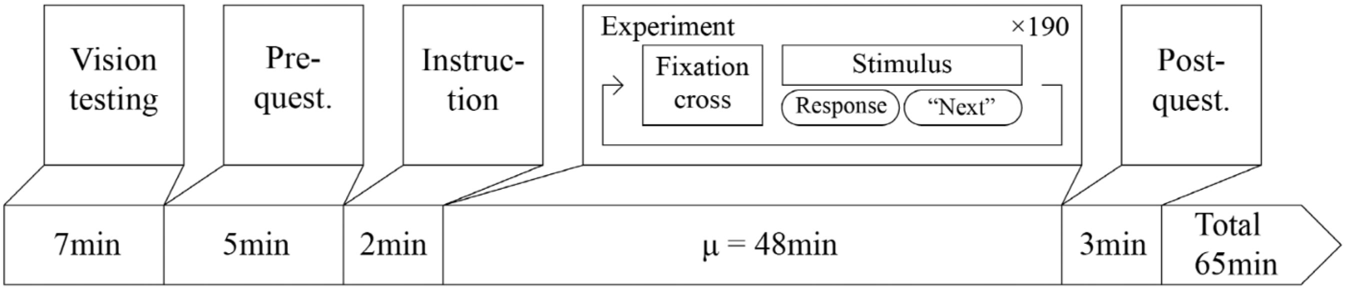

Fig. 1. Experiment course.

Fig. 2. Experimental setup.

The participants' task was to evaluate their overall viewing experience (including overall opinions about image quality), naturalness, and depth perception on a scale from 1-poor to 9-excellent after each image. The three qualities were selected on the basis of previously published results related to stereoscopic viewing experience and image quality attributes (I3A 2007)[56] The viewing duration of the images was not limited, and a fixation cross (zero disparity) was displayed for one second before the next image. Participants answered the quality questions using a keyboard. In total, each participant evaluated 190 images presented in randomized order (5 contents x 2 repetitions x (1 original + 18 color manipulated images)). The viewing distance (40 cm) and angle were controlled by the chin and forehead rest (Fig. 2). To avoid interaction between illuminance and color perception, the images were viewed in a darkened laboratory[57]. After the task, the participants and the test leader had the opportunity to ask questions and comment on the experiment. Participants who had personal eyeglasses wore them during the tests. In total, a testing session lasted one hour.

Fig. 3 Images used in the test: "Bus stop" (1) (first on the left), "Adults" (2), "Graffiti" (3)', "Boy" (4), and "Friends" (5).

2.3. Stimuli

The images used in the test were selected on the basis of recommendations for objective characterization of camera attributes and subjective image quality experiments (International Imaging Industry Association I3A[56]). In total, five different natural images with different content were used (see Fig. 3), and each of these images corresponded to specific clusters in the camera phone photospace (a statistical description of the frequency of picture-taking as a function of subject illumination level and subject-to-camera distance): "Bus stop" corresponded to a typical scene described as scenic landscapes/large groups in cloudy bright to sunny lighting conditions; "Adults" presented a cluster described as a close-up in typical indoor lighting conditions; "Graffiti" showed a small group in dim-dark lighting conditions; "Boy" referred to a close-up in dim-dark lighting conditions; and "Friends" corresponded to a small group in cloudy-bright to sunny lighting conditions[56].

Each image was 800 pixels wide and 480 pixels high, and the left- and right-eye images were presented side by side on the display so that the left and the right eye could see the left and the right eye images, respectively, through the stereoscope. In all scenes, the foreground objects were on the zero disparity level and the majority of the scene points were located behind the screen level. The disparity range was less than one degree of visual angle.

The minimum and the maximum values of each of the three color components (RGB) for the original images named "Bus stop", "Adults", "Graffiti" and "Friends" were 0 and 255, respectively, while for the original image "Boy", the minimum value of all color components was 0 and the maximum value of all 3 color stimuli was 210. The images presented on the right side of the display were kept unchanged, whereas the colors of the left eye image were adjusted. The resulting adjusted test images were obtained from the original images by linearly compressing one of the color components as follows:

$$C_{outi} = i\ x\ C_{in},\ with\ i = 0.4,\ 0.5,\ 0.6,\ 0.7,\ 0.8,\ 0.9 \qquad (1)$$

where C_{outi} represents the compressed red, green or blue color component of the output image, and C_{in} is the corresponding color component of the original input image.

In this manner, it was possible to test the influence of the sensitivity decrease of each color component on the subjective evaluation of the stereo image quality.

2.3.1. Distortion characterization

Table 1. Mean ΔE_{00} values for different channel multipliers for red, green, and blue.

Color Channel	Channel multiplier	Mean ΔE_{00}
Red	1	0
	0,9	3,62
	0,8	6,82
	0,7	9,55
	0,6	11,94
	0,5	13,68
	0,4	15,12
Green	1	0
	0,9	2,67
	0,8	5,01
	0,7	7,03
	0,6	8,88
	0,5	10,5
	0,4	11,9
Blue	1	0
	0,9	2,92
	0,8	5,54
	0,7	8,09
	0,6	10,37
	0,5	12,34
	0,4	14,1

Colors from the GretagMacbeth ColorChecker were used to characterize the color distortions. The ColorChecker is comprised of 24 patches of colors occurring in natural scenes. The ColorChecker colors from the CIELAB color space were converted to RGB space using the display white point, and then each color was measured with a PR-670 SpectraScan spectroradiometer (Photo Research, Chatsworth, CA, USA). All 24 colors were measured in all 18-color distortion conditions for a total of 456 measurements. The measurements were taken through the stereoscope at a 40-cm distance. In the next step, the CIEDE2000 color difference ΔE_{00}[58] value was computed for each distorted color using the implementation by Sharma, Wu & Dalal[59], and the ΔE_{00} values were averaged within each distortion. The CIEDE2000 model describes the perceptual difference between two colors, in this case, the original and the distorted. See Table 1 for the distortions measured in ΔE_{00}.

2.4. Participants

A total of 20 participants, 12 men and 8 women, participated in the test. All participants had normal or corrected-to-normal near and far visual acuity (LEA tests), stereo acuity of 120 sec-arc or better (TNO test for stereoscopic vision), no problems with color vision (Ishihara's test), and near horizontal phoria between 7 D eso and 13 D exo (Maddox wing). Eight participants wore glasses during the tests. The mean age of the participants was 27.9 years, and all participants were familiar with 3D media applications.

3. Results and discussion

Because of the nature of the data, nonparametric statistical procedures were used for the data analyses. The Holm-Bonferroni correction was used to control for the occurrence of false positive p-values (a 0.05 threshold value was used).

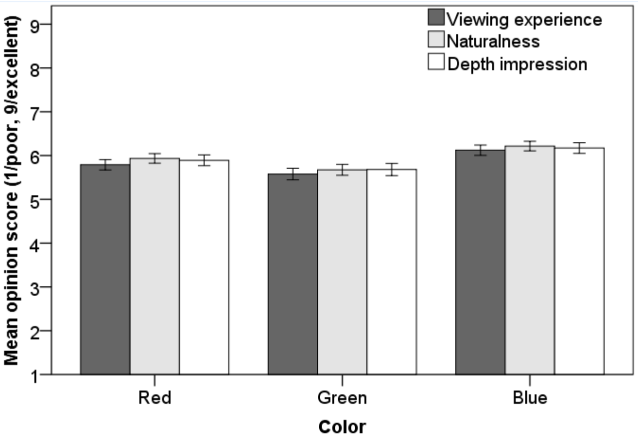

Fig. 4. Overall comparison of color groups: mean opinion scores for overall viewing experience, naturalness, and depth perception. Vertical lines represent error bars; confidence interval level of 95%.

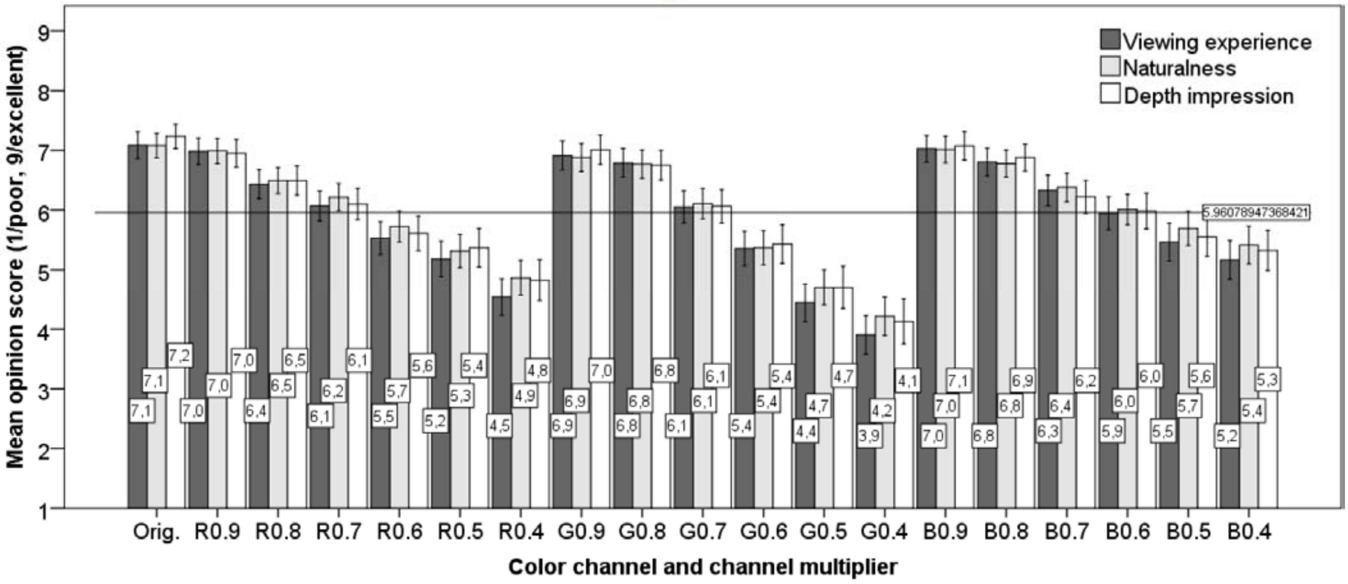

Fig. 5. Mean opinion scores for color channel multipliers. Vertical lines represent error bars, confidence interval level 95%. Reference line presents median of the data.

3.1. Overall comparison

The Kruskal-Wallis test revealed significant differences between the color channels for evaluation of viewing experience (χ^2 (2) =34.44, p=0.000), naturalness (χ^2 (2) =35.73, p=0.000), and depth perception (χ^2 (2) =22.38, p=0.000). Pair-wise comparison (Mann-Whitney U) between the G and R results showed no significant differences in the evaluated qualities (Figs. 4 and 5). Comparisons between B and G revealed significant differences in all three qualities evaluated: the decrease in B had a smaller effect on the overall viewing experience of the images (Z=-5.579, p=0.000), naturalness (Z=-5.793, p=0.000), and depth perception (Z=-4.475, p=0.000).

Similar to the results of the B and G comparison, the scores given for the overall viewing experience (Z=-4.194, p=0.000), naturalness (Z=-3.879, p=0.000), and depth perception (Z=-3.394, p=0.001) differed significantly when the B and R data were compared: a decrease in B had less influence on the image-quality related features than a decrease in R.

Thus, even though only the values of one color channel were varied at time, the combinations of cone responses to different wavelengths were changed, which in turn affected the perceived scene lightness, hue and colorfulness, and overall color appearance[24,26,27] As a result, changes in the color combinations may have had some effect on the visibility of small details, reflections, and shadows[10,19]; at certain points, some of the color attributes no longer corresponded to the prior expectations, which decreased the overall viewing experience, image naturalness, and perceived depth, as expected[31, 32, 42, 60]. Because the color changes also affected the perceived depth levels, our results support the view that color interacts with other image attributes and supports depth perception in particular if these attributes are relevant for the task performance[19-22, 31, 34].

3.2. Comparison of single color combinations

The Kruskal-Wallis test revealed significant differences in the scores for viewing experience, naturalness, and depth perception between the different channel multipliers within specific color channels (Table 2). A more detailed analysis of the data, including comparison of the original and color-adjusted images, showed that most of the color channel changes had some impact on the evaluated qualities. As Fig. 5 shows, a decrease in a specific color channel affected the subjective opinions when a channel decrease of 20% of the original color component was used (Table 3). If we assume that the lowest acceptable threshold is near 6 on the scale from 1 (poor) to 9 (excellent) (overall mean 5.96 and median 6.065), then channel multipliers lower than 0.7 should be avoided to guarantee satisfactory image quality.

Similar to the results from general color comparisons (see Section 3.1.), certain color channel changes were more acceptable than others. Small changes in the ΔE_{00} values had a relatively similar effect on the evaluated image qualities regardless of the color channel, whereas larger increases in ΔE_{00} values in the B and R channels did not affect image quality as much as changes in the G channel[31, 32, 42, 60]. Because changes in color-specific channels also affected perceived depth levels differently, it might be possible that, in addition to other color-depth interactions, specific color channels also have different influence on binocular fusion[20-23]. However, more studies with accurately controlled parameter setups are needed before assumptions about color channel influence can be supported.

Table 2. Significant changes between single color combinations within color groups.

Color	Procedure	Viewing experience	Naturalness	Perceived depth
Red	Chi-Square	233,532	208,790	177,506
	df	6	6	6
	Asymp. Sig.	,000	,000	,000
Green	Chi-Square	339,791	305,906	254,976
	df	6	6	6
	Asymp. Sig.	,000	,000	,000
Blue	Chi-Square	149,346	122,242	132,498
	df	6	6	6
	Asymp. Sig.	,000	,000	,000

3.3. Influence of content on subjective opinions

In addition to color channel comparisons, the influence of different image content was studied. As shown in Fig 6, the image content had a clear influence on how the evaluated image qualities were affected. The Kruskal-Wallis test revealed significant differences between the viewing experience (χ^2 (4) =68.08, p=0.000), naturalness (χ^2 (4) =119.17, p=0.000), and depth perception (χ^2 (4) =70.81, p=0.000). Pair-wise comparison of image content showed that all contents differed significantly from each other (see Table 4 and Fig. 6), except for Bus stop/Boy and Graffiti/Friends.

Table 3 Pair-wise comparison of different channel multipliers within specific color channels. Only significant changes are presented.

Color	Pair	Procedure	Viewing experience	Naturalness	Perceived depth
Red	**Orig./0.8**	Mann-Whitney	15604,500	15674,000	15153,000
		Wilcoxon W	35704,500	35774,000	35253,000
		Z	-3,871	-3,819	-4,276
		Asymp. Sig.	,000	,000	,000
	Orig./0.7	Mann-Whitney	13408,000	13904,000	13004,000
		Wilcoxon W	33508,000	34004,000	33104,000
		Z	-5,787	-5,372	-6,154
		Asymp. Sig.	,000	,000	,000
	Orig./0.6	Mann-Whitney	11004,500	11684,000	11005,000
		Wilcoxon W	31104,500	31784,000	31105,000
		Z	-7,881	-7,300	-7,894
		Asymp. Sig.	,000	,000	,000
	Orig./0.5	Mann-Whitney	9896,000	9954,500	10645,500
		Wilcoxon W	29996,000	30054,500	30745,500

		Z	-8,838	-8,801	-8,201
		Asymp. Sig.	,000	,000	,000
	Orig./0.4	Mann-Whitney	7424,500	8197,000	8756,000
		Wilcoxon W	27524,500	28297,000	28856,000
		Z	-10,974	-10,322	-9,831
		Asymp. Sig.	,000	,000	,000
Green	**Orig./0.7**	Mann-Whitney	13845,000	13924,500	13290,500
		Wilcoxon W	33945,000	34024,500	33390,500
		Z	-5,408	-5,347	-5,898
		Asymp. Sig.	,000	,000	,000
	Orig./0.6	Mann-Whitney	10483,500	10241,500	11117,000
		Wilcoxon W	30583,500	30341,500	31217,000
		Z	-8,330	-8,557	-7,782
		Asymp. Sig.	,000	,000	,000
	Orig./0.5	Mann-Whitney	7352,000	7536,000	8722,000
		Wilcoxon W	27452,000	27636,000	28822,000
		Z	-11,040	-10,896	-9,857
		Asymp. Sig.	,000	,000	,000
	Orig./0.4	Mann-Whitney	5752,500	6548,000	7544,500
		Wilcoxon W	25852,500	26648,000	27644,500
		Z	-12,423	-11,739	-10,876
		Asymp. Sig.	,000	,000	,000
Blue	**Orig./0.7**	Mann-Whitney	15199,500	15405,500	14250,000
		Wilcoxon W	35299,500	35505,500	34350,000
		Z	-4,225	-4,050	-5,064
		Asymp. Sig.	,000	,000	,000
	Orig./0.6	Mann-Whitney	13221,000	13287,500	13331,000
		Wilcoxon W	33321,000	33387,500	33431,000
		Z	-5,953	-5,905	-5,863
		Asymp. Sig.	,000	,000	,000
	Orig./0.5	Mann-Whitney	11653,000	12224,000	11625,000
		Wilcoxon W	31753,000	32324,000	31725,000
		Z	-7,310	-6,823	-7,343
		Asymp. Sig.	,000	,000	,000
	Orig./0.4	Mann-Whitney	10287,500	11442,500	10880,500
		Wilcoxon W	30387,500	31542,500	30980,500
		Z	-8,493	-7,505	-7,991
		Asymp. Sig.	,000	,000	,000

Table 4. Pair-wise comparison of content influence on subjective opinions. Only significant changes are presented.

Pair	Statistics	Viewing experience	Naturalness	Depth perception
Boy/Friends	Mann-Whitney U		243514,00	252901,00
	Wilcoxon W		532694,00	542081,00
	Z		-5,37	-4,24
	Asymp. Sig.		0,00	0,00
Boy/Graffiti	Mann-Whitney U	256385,50	236814,00	251075,50
	Wilcoxon W	545565,50	525994,00	540255,50
	Z	-3,84	-6,17	-4,46
	Asymp. Sig.	0,00	0,00	0,00
Boy/Adults	Mann-Whitney U	248744,50	251823,50	258630,00
	Wilcoxon W	537924,50	541003,50	547810,00
	Z	-4,73	-4,37	-3,56
	Asymp. Sig.	0,00	0,00	0,00
Adults/Friends	Mann-Whitney U	238734,00	217122,00	233315,00
	Wilcoxon W	527914,00	506302,00	522495,00
	Z	-5,91	-8,46	-6,54
	Asymp. Sig.	0,00	0,00	0,00
Bus stop/Friends	Mann-Whitney U		262283,50	261158,50

	Wilcoxon W		551463,50	550338,50
	Z		-3,14	-3,27
	Asymp. Sig.		0,00	0,00
Bus stop/Graffiti	Mann-Whitney U	256415,00	257070,00	259953,50
	Wilcoxon W	545595,00	546250,00	549133,50
	Z	-3,83	-3,76	-3,41
	Asymp. Sig.	0,00	0,00	0,00
Bus stop/Adults	Mann-Whitney U	257297,50	244676,00	259282,00
	Wilcoxon W	546477,50	533856,00	548462,00
	Z	-3,71	-5,20	-3,48
	Asymp. Sig.	0,00	0,00	0,00
Adults/Graffiti	Mann-Whitney U	224014,50	209873,50	229055,50
	Wilcoxon W	513194,50	499053,50	518235,50
	Z	-7,65	-9,32	-7,05
	Asymp. Sig.	0,00	0,00	0,00

Fig. 6. Mean opinion scores for different contents. Vertical lines represent error bars (confidence interval level of 95%) and horizontal lines represent the overall median.

As expected on the basis of previously published results, the close-up-type content (subject-camera distance approximately 1 m; "Adults") of human faces was the most sensitive scene; all color-channel-specific changes affected the evaluated scene qualities[41, 42]. Additionally, landscape-type images with light backgrounds (as in the "Bus stop" and close-up-type images) and a clearly distinguishable target-background combination (as in "Boy") were more sensitive to the changes in the G channel than to changes in the R or B channels. Natural scenes with greenish or brownish backgrounds, as in "Graffiti" and "Friends", were less sensitive to channel changes, particularly when changes were made to the B channel[31, 32, 38, 40].

4. Conclusions

Over the years, several image attributes have been shown to have an influence on image quality and naturalness. Changes in colors and stereoscopic depth levels may increase the realism of the scene by increasing the evaluated naturalness levels, but they also have important role in creating the overall viewing experience.

Twenty participants were asked to evaluate different natural stereoscopic scenes in which the values of the red, green, and blue color channels were decreased systematically. A decrease in blue channel values clearly had a lesser effect on the evaluated image quality, whereas a decrease in the green channel values was more noticeable, particularly when the targets or backgrounds of the scenes were lighter in color or the target was well distinguished from the background. As expected, the content that presented human faces was clearly the most vulnerable to the color channel changes, whereas landscape-type images with greenish or brownish backgrounds were more tolerant to color changes.

Interestingly, the color changes affected not only the overall image experience and naturalness but also the depth perception of the scenes. It has been shown that colors may assist in binocular fusion, but it could be possible that color-channel-specific changes also have some influence on depth perception.

In general level, color-channel-specific changes that were less than 30% from the original values seem to be acceptable with all three color channels, and overall viewing experience, naturalness, and depth perception remain relatively satisfactory. In some cases, particularly with the red and blue channels, larger color-specific channel changes could also be used, but the quality and acceptability depends on the content features.

Therefore, it seems that some color-channel-specific asymmetry combinations are well tolerated in stereoscopic content and could be used in stereo-coding algorithms. However, similar asymmetries could be used in stereoscopic applications without color corrections. Because there are clear differences in the evaluation criteria between scene contents, the nature of the content should be taken into account when color-channel-specific changes are used in rendering of stereoscopic content. In our tests, only natural scenes were evaluated, and thus it is possible that the acceptability criteria for synthetic content are different. However, similar to the natural content, we can assume that if users have some color-specific expectations about targets or backgrounds, the scene quality is evaluated on the basis of similar principles.

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