Effects of Colors on the Eyestrain under a Virtual Environment

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Abstract. In this study, we focus on the effects of color on eyestrain under virtual environments. We constructed three kinds of virtual spaces in which all walls and objects have identical colors. Twelve volunteer subjects continuously gazed stereoscopically at the inside of each space for 15 minutes. The experiments clarified that the degree of eyestrain differs between the colors of the space. Additionally, we compared the different effects of color on eyestrain between gazing at virtual spaces and plain images.

Introduction

In recent years, many interactive systems using virtual reality have been developed and utilized for various fields including medicine and entertainment. However, these systems sometimes cause eyestrain or other problems that resemble motion sickness (Hirayanagi, 2006; Nakagawa and Ohsuga, 1998). Therefore, we focused on eyestrain and clarified its mechanism by various experiments. Color is one factor that causes eyestrain in real space (Ohta, 1985), specifically, successive contrast, simultaneous color contrast, and a color's wavelength. However, in virtual space, the relation of color and eyestrain remains unclear. Therefore, we concentrated on the effects of color that cause eyestrain in virtual space and measured the following:

(1) eyestrain caused by color in virtual space
(2) eyestrain using plane images
(3) eyestrain caused by color in simpler virtual space than that used in (1)

Construction of experimental system

Figure 1 shows the constructed experimental system in which we generated a virtual space by computer and reflected it onto a 100-inch screen with two polarizing plate installed projectors. Subjects wore polarizing glasses to enable a stereoscopic view. We employed a straight line polarization system and installed it in a darkroom without external light.

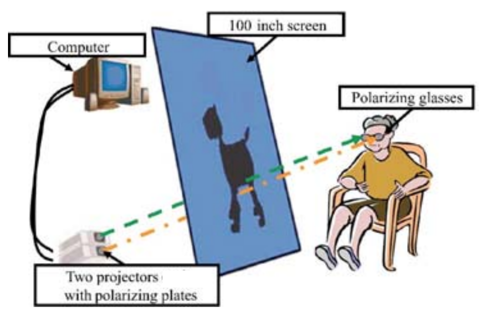

Figure 1. Experimental system

Eyestrain measurement by color in virtual space

Outline of experiment. This experiment clarified whether color influences eyestrain in virtual space and which color excessively affects eyestrain. Subjects were instructed to intently watch a virtual space that consisted of one color for 15 minutes, and their eyestrain was measured before and after.

In real space, since eyes get more tired looking at a color of longer wavelength (Ohta, 1985; The Color Science Association of Japan, 1993), we used red as a long wavelength, purple as a short wavelength, and green as an in between wavelength.

In the center of the virtual space we put a solid figure that changed form at certain time intervals and asked subjects to count the number of changes while continuing to stare at the space. An example of our virtual space is shown in Figure 2. We used flicker value and a questionnaire to measure eyestrain. Flicker value is defined as the threshold frequency of the on and off light changes until they cannot be detected by the subjects. We measured flicker values three times per subject and calculated the averages.

For questionnaires, the following eyestrain-related items of the Oculomoter of Simulator Sickness Questionnaire (Kennedy *et al.*, 1998) were employed:

(1) General discomfort
(2) Fatigue
(3) Headache
(4) Eyestrain
(5) Focusing difficulty
(6) Concentrating difficulty
(7) Blurred vision

Subjects reported the degree to which they experienced each of the symptoms as “not at all,” “slightly,” “moderately,” and “severely” in score of 0, 1, 2, and 3, respectively. We also asked the subjects who felt eyestrain to speculate about its causes.

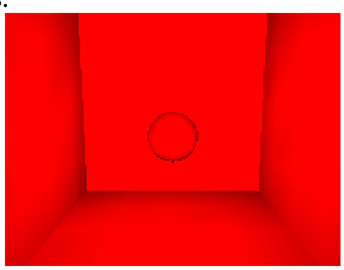

Figure 2. Example of virtual space

Experimental method.

(1) A subject answers a questionnaire
(2) He/she takes a flicker test
(3) He/she continues stereoscopic staring at the virtual space for 15 minutes and counts the number of changes of the solid figure’s form.
(4) He/she takes another flicker test
(5) He/she records the number of changes of the solid figure’s form
(6) He/she answers another questionnaire

Experimental results. 12 student subjects (8 males) served as volunteers.

Figure 3 shows an example of the experimental scene, and Figures 4, 5, and 6 show the experimental results. Almost all subject’s flicker value declined for all colors in comparisons between before/after gazing at the space. To confirm the statistical significance of the decline, we examined the paired difference tests of flicker values before/after gazing for each color. Tables 1, 2 and 3 show the results (*denotes that the P-value is less than 0.05, that is, statistically significant at the 0.05 level, and ** denotes that the P-value is less than 0.01, that is, statistically significant at the 0.01 level.). From these results, the existence of eyestrain in virtual space was confirmed in all colors.

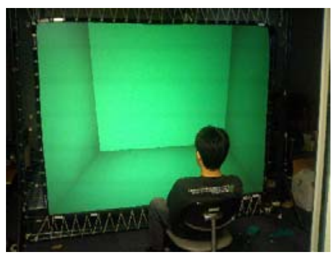

Figure 3. Experimental scene

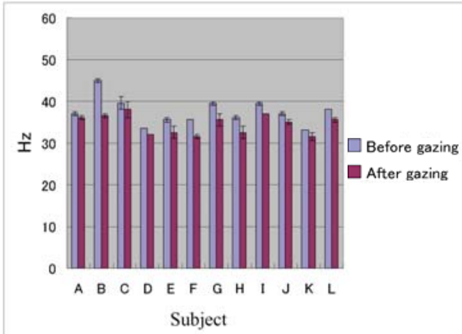

Figure 4. Flicker values before/after gazing at red space

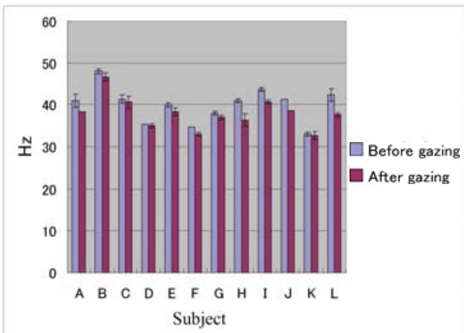

Figure 5. Flicker values before/after gazing at green space

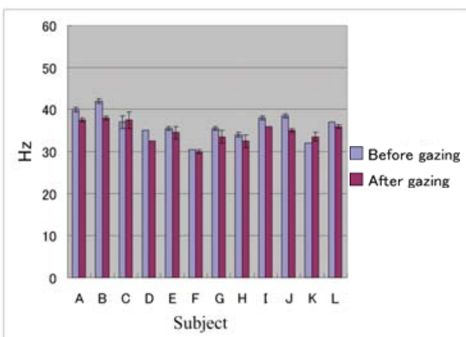

Figure 6. Flicker values before/after gazing at purple space

Table 1. Flicker value difference in red space

Variable	Before gazing	After gazing	Difference			Gudge
Sample	12			Statistic: t	4.126	
Mean value	41.111	39.583	1.528	Degree of freedom	11	
Unbiased variance	23.259	19.194		Both sides p value	0.002	**
Standard deviation	4.823	4.381		One side p value	0.001	**

Table 2. Flicker value difference in green space

Variable	Before gazing	After gazing	Difference			Gudge
Sample	1			Statistic: t	4.716	
Mean value	39.972	37.917	2.056	Degree of freedom	1	
Unbiased variance	17.423	14.205		Both sides p value	0.001	**
Standard deviation	4.174	3.769		One side p value	0.000	**

Table 3. Flicker value difference in purple space

Variable	Before gazing	After gazing	Difference			Gudge
Sample	12			Statistic: t	4.700	
Mean value	39.556	38.056	1.500	Degree of freedom	11	
Unbiased variance	21.300	18.987		Both sides p value	0.001	**
Standard deviation	4.615	4.357		One side p value	0.000	**

We confirmed the differences of eyestrain among colors by analysis of variance assuming color as a factor for normalized flicker values, where normalized flicker value is defined by the following expressions. Results show that eyestrain is stronger, so the value is smaller:

$$\text{Normalized flicker value} = \frac{\begin{array}{c}\text{Flicker value}\\ \text{After gazing at the space}\end{array}}{\begin{array}{c}\text{Flicker value}\\ \text{Before gazing at the space}\end{array}}$$

Table 4. Analysis of variance of normalized flicker values assuming color as a factor

Factor	Sum of squares	Degree of freedom	Mean square	F value	P value	Gudge
Color	0.001	2	0.001	0.782	0.466	
Error	0.031	33	0.001			
Whole	0.032	35				

The result of the analysis of variance for normalized flicker values shows that the main effect was not significant (Table 4). However, comparing the mean normalized flicker value (averaged value of normalized flicker value of all subjects) of each color, we obtained the following order of the colors of spaces (Figure 7):

$$green < purple \approx red.$$

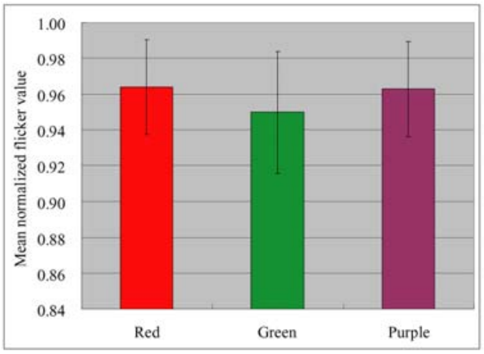

Figure 7. Mean normalized flicker value of each color

This result shows that green causes the most eyestrain, which is different from the tendency in real space where the color of longer waves such as red causes more eyestrain (The Color Science Association of Japan, 1993). After considering the contradiction, we offered the following two hypotheses: 1) The brightness of green may be higher than the others. 2) Eyestrain may vary by object for stereoscopic views. We examined these hypotheses one by one below.

Eyestrain measurement using plane image

Outline of experiment. We tested hypothesis 1 (Brightness of green may be high in comparison with others) by measuring the effect of eyestrain only caused by color by showing two-dimensional plane images instead of 3-dimensional stereoscopic images. The colors, measurement method of eyestrain, and experimental procedure used in this experiment were identical as above.

Experimental results. 12 student subjects (8 males) volunteered. Figures 8, 9, and 10 show the experimental results of each color. Analyses were identical as in the above experiment. Results of the paired difference tests of flicker value before/after gazing are shown in Tables 5, 6, and 7. Flicker value before gazing at virtual space was significantly different from after gazing. For the analysis result of variance for normalized flicker value, the main effect of color was not significant (Table 8).

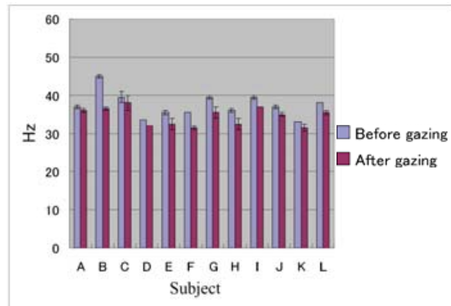

Figure 8. Flicker values before/after gazing at red plane

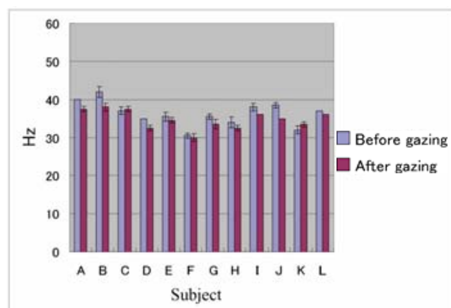

Figure 9. Flicker values before/after gazing at green plane

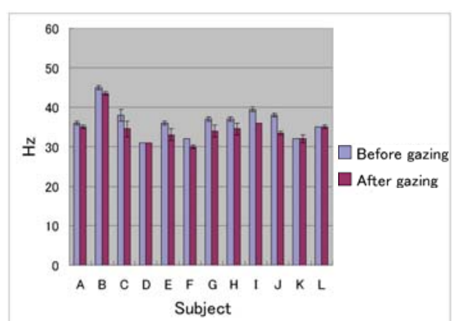

Figure 10. Flicker values before/after gazing at purple plane

Table 5. Flicker value difference in red plane

Variable	Before gazing	After gazing	Difference			Gudge
Sample	12			Statistic: t	5.082	
Mean value	37.417	34.458	2.958	Degree of freedom	11	
Unbiased variance	10.492	5.384		Both sides p value	0.000	**
Standard deviation	3.239	2.320		One side p value	0.000	**

Table 6. Flicker value difference in green plane

Variable	Before gazing	After gazing	Difference			Gudge
Sample	12			Statistic: t	3.394	
Mean value	36.250	34.708	1.542	Degree of freedom	11	
Unbiased variance	10.477	5.884		Both sides p value	0.006	**
Standard deviation	3.237	2.426		One side p value	0.003	**

Table 7. Flicker value difference in purple plane

Variable	Before gazing	After gazing	Difference			Gudge
Sample	12			Statistic: t	4.580	
Mean value	36.375	34.333	2.042	Degree of freedom	11	
Unbiased variance	14.506	11.424		Both sides p value	0.001	**
Standard deviation	3.809	3.380		One side p value	0.000	**

Table 8. Analysis of variance of normalized flicker value assuming color as a factor

Factor	Sum of squares	Degree of freedom	Mean square	F value	P value	Gudge
Color	0.010	2	0.005	2.799	0.077	
Error	0.055	30	0.002			
Whole	0.065	32				

By comparing the mean normalized flicker value of each color, we obtained the following order of the colors of planes:

$$red < purple < green.$$

Red causes the most eyestrain (Figure 11).

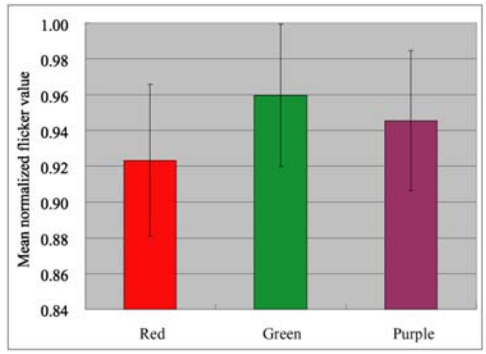

Figure 11. Mean normalized flicker value of each color

Comparing this result with the result of the preceding experiment, a contradiction exists: in this experiment green did not cause the most eyestrain, which refutes hypothesis 1.

Eyestrain measurement by color in simpler virtual space than that used in the first experiment

Outline of experiment. In the first experiment we employed virtual space with a solid figure that subjects continued to closely watch. However, perhaps the eyestrain influence was caused by the stereoscopic view of the solid figure. In addition, influence may vary by object. Therefore in our third experiment, we removed the solid figure from the virtual space used in the first experiment and showed the space without a solid figure to the subjects. The colors, measurement method of eyestrain, and experimental procedure were identical to the previous experiments.

Experimental results. 12 student subjects (8 males) volunteered. Figures 12, 13, and 14 show the experimental results for each color. Analyses are identical as previous experiments. The results of the paired difference tests of flicker value before/after gazing are shown in Tables 9, 10, and 11. Flicker value before gazing at the virtual space was significantly different than after gazing. For the result of the analysis of variance for normalized flicker values, the main effect of color was not significant (Table 12).

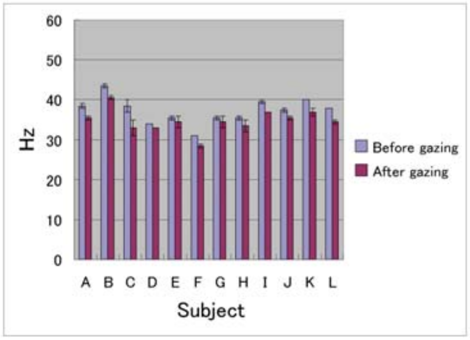

Figure 12. Flicker values before/after gazing at red space

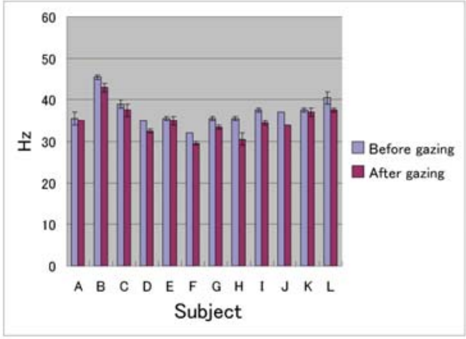

Figure 13. Flicker values before/after gazing at green space

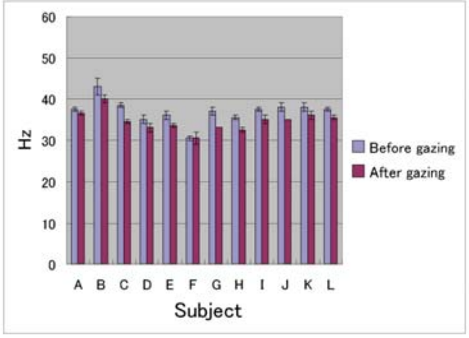

Figure 14. Flicker values before/after gazing at purple space

Table 9. Flicker value difference in red space

Variable	Before gazing	After gazing	Difference			Gudge
Sample	12			Statistic: t	6.770	
Mean value	37.250	34.750	2.500	Degree of freedom	11	
Unbiased variance	10.386	8.295		Both sides p value	0.000	**
Standard deviation	3.223	2.880		One side p value	0.000	**

Table 10. Flicker value difference in green space

Variable	Before gazing	After gazing	Difference			Gudge
Sample	12			Statistic: t	5.786	
Mean value	37.167	34.958	2.208	Degree of freedom	11	
Unbiased variance	11.515	12.794		Both sides p value	0.000	**
Standard deviation	3.393	3.577		One side p value	0.000	**

Table 11. Flicker value difference in purple space

Variable	Before gazing	After gazing	Difference			Gudge
Sample	12			Statistic: t	7.635	
Mean value	36.955	34.409	2.545	Degree of freedom	11	
Unbiased variance	9.023	5.941		Both sides p value	0.000	**
Standard deviation	3.004	2.437		One side p value	0.000	**

Table12. Analysis of variance of normalized flicker value assuming color as a factor

Factor	Sum of squares	Degree of freedom	Mean square	F value	P value	Gudge
Color	0.000	2	0	0.124	0.884	
Error	0.036	33	0.001			
Whole	0.037	35				

However, comparing the mean normalized flicker value of each color, we obtained the following order of the colors of spaces:

$$red \approx purple < green.$$

Red caused the most eyestrain (Figure 15).

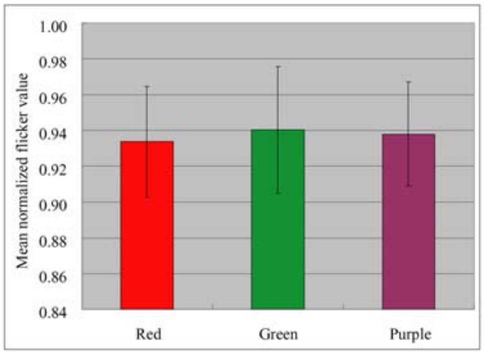

Figure 15. Mean normalized flicker value of each color

Comparing this result with the first experiment's result, green caused the most eyestrain in the first experiment, but not in this experiment. Hypothesis 2 is considered possible.
Table 13 shows the normalized flicker value obtained from the results of all three experiments.

Table 13. Normalized flicker value for each experiment and color

	First experiment	Second experiment	Third expeirment
Red	0.96	0.92	0.93
Green	0.95	0.96	0.94
Purple	0.96	0.95	0.94
S.D.	0.008	0.018	0.003

This table shows that the dispersions of worsening eyestrain between colors in virtual spaces, as the results of the first and last experiments, are smaller than between colors in 2-dimensional plane, as the result of the second experiment. This suggests that the difference of eyestrain between colors becomes smaller when gazing at virtual space in stereoscopic view compared with gazing at a 2-dimensional plane.
Table 14 shows the number of subjects whose eyestrain worsened after gazing in the second and last experiments, where the number of subjects whose eyestrain worsened is the number of subjects whose total question items score increased after gazing compared with total score before gazing.

Table 14. Subjects whose eyestrain worsened

	Second experiment	Third expeirment
Red	10	5
Green	7	5
Purple	5	7

In the second experiment that showed 2-dimensional planes, the number of subjects whose eyestrain worsened was remarkably large after gazing at the red plane. On the other hand, we found no such difference between colors in the last experiment showing virtual spaces.
This comparison suggests that the difference of eyestrain between colors becomes smaller when gazing at virtual spaces in stereoscopic view compared with gazing at 2-dimensional planes, which matches the result obtained from Table 13.

Discussion

In the first experiment we measured eyestrain caused by gazing at colors in virtual spaces. The results showed that green caused the most eyestrain. Considering the contradiction between the obtained result and the tendency in real space, we offered the following two hypotheses: 1) The brightness of green may be high in comparison with others, and 2) Eyestrain may vary with object for stereoscopic views. We examined these hypotheses in two experiments.
The results of the second experiment, which showed 2-dimensional planes, refuted hypothesis 1.
The results of the third experiment, which showed virtual spaces from which the solid figures used in the first experiment were removed, differed from the first experiment, suggesting that eyestrain may change between objects for stereoscopic view.
In addition, the difference of eyestrain between colors becomes smaller when stereoscopically gazing at a virtual space

compared with gazing at a 2-dimensional plane.

Conclusions

We performed experiments to clarify the condition of color that causes eyestrain in virtual space. The experimental results show that the effect of colors that causes eyestrain is smaller when gazing in virtual space compared in real space.
Future work will clarify the occurrence mechanism of eyestrain by other factors than color.

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