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Eye Movement Measurement of Gazing at the Rim of a Column in Stereo Images with Yellow-Blue Equiluminance Random Dots

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SUMMARY We studied the detection of the incongruence between the two eyes' retinal images from occlusion perception. We previously analyzed the evasion action caused by occlusion by using green-red equiluminance, which is processed by parvocellular cells. Here we analyzed this action by using yellow-blue equiluminance, which is said to be treated by koniocellular cells and parvocellular cells. We observed that there were the cases in which the subject could perceive incongruence by the occlusion and other cases in which the subject could not perceive it. Significant differences were not seen in all conditions. Because a difference was seen in an evasion action at the time of the rim occlusion gaze when we compare the result for the yellow-blue equiluminance with the green-red equiluminance, it is suggested that the response for each equiluminance is different. We were able to clarify the characteristic difference between parvocellular cells and koniocellular cells from an occlusion experiment.

key words: *occlusion, parvocellular cells, koniocellular cells, equiluminance*

1. Introduction

Stereoscopic vision has been studied for many decades. A stereoscope was invented in 1832 by Charles Wheatstone. An anaglyph was developed in 1853 by Wilhelm Rollman, and a movie using an anaglyph was shown by Joseph D'Almeida. Edwin Herbert Land developed a polarizing plate in 1932, after which the use of stereoscopic vision with a polarizing filter as entertainment spread widely [1].

Stereoscopic vision technology is applied to fields other than entertainment. For example, Kokojima et al. developed a naked-eye 3D display for medical use [2], and the Housing Presentation System (ALTA) using a head-mounted display was developed by Computer Systems Technology as a house presentation system [3].

The stereoscopic vision is used to perceive the depth direction in the everyday life. Because our eyes are separated horizontally, disparity occurs; stereoscopic vision is enabled by this disparity, which is simply difference between the left eye's image and the right eye's image. The detection of congruence or incongruence of the two eyes' retinal images is thus necessary for stereoscopic vision using the disparity. However, we cannot always recognize to detect congruence or incongruence of the eyes' retinal images because a phenomenon called "occlusion" can prevent this detection of the congruence/incongruence.

Here, we explain three types of occlusion as shown in Fig. 1. The first type is the phenomenon in which an object on one side covers an object behind it. The second one is when an object itself covers its own plane. The third one is the phenomenon in which an object with a curved surface covers its own aspect.

We have studied this third type of occlusion, which is called "rim occlusion" [4], [5]. We conducted the present study to elucidate the functions of parvocellular cells and koniocellular cells in the lateral geniculate nucleus (LGN) of the human brain by conducting occlusion perception experiments.

We will describe the perception processing mechanism of the brain. The information received by each retina is sent to the LGN. The visual information of the left visual field is processed by the right LGN, and that of the right visual field is processed by the left LGN. The LGN has six layers consisting of three types of cells: large cells (the magnocellular layer), small cells (the parvocellular layer), and granule cells (the koniocellular layer). The large cells comprise layers I and II; the small cells comprise layers III-VI, and the koniocellular cells are the extremely small cells located between the large and small cells. Magnocellular-layer cells have good temporal resolution and detect movement and depth based on luminance. Parvocellular cells' temporal resolution is slow, but they detect hue and chrominance. The koniocellular cells' temporal resolution is slower than that of magnocellular cells and faster that of parvocellular cells and these cells are reported to detect hue and chrominance, as do parvocellular cells [6], [7].

From the view of chrominance pathways, we will describe them briefly. Parvocellular cells process green-red combinations. Koniocellular cells process 'blue-on' cells. Bistratified cells (which were first identified relatively recently) are projected on the geniculocortical granule cell layer (i.e., the koniocellular layer). They process S-cones, with sensitivity for blue [8]. Some papers have indicated that the opponent colors of blue (red and green) or blue-yellow are processed in parvocellular cells [9], [10] before blue-on cells were reported as the third pathway through koniocellular cells [11].

It is suspected that the various types of visual infor-

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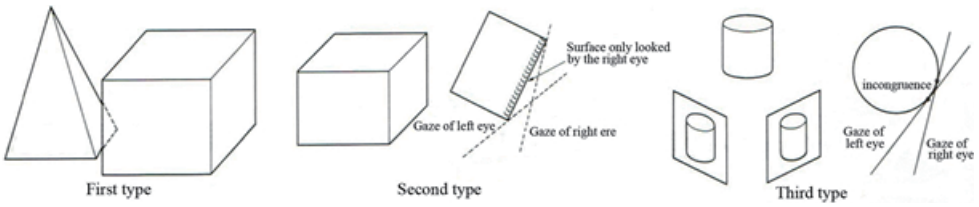

Fig. 1 Three types of occlusion [4].

mation are processed only by the corresponding cells [12]. Kingdom et al. performed an experiment in which an equiluminance illusion drawing was used, and they argued that the perception of luminance and the perception of chrominance are processed at the same time [13].

As another aspect of visual information processing pathway, magnocellular layer cells treat depth perception as previous described. If we observe a random dot stereogram with black and white dots, stereoscopic vision provided by both eyes will detect the eyes' congruence or incongruence of the retinal images. The disparity between the two eyes' corresponding images is then estimated, which leads to depth perception. We hypothesized that the mechanisms underlying the brain's ability to detect congruence or incongruence of the eyes' retinal images could be clarified by an evaluation of the avoidance behavior of binocular eye movements when rim occlusion occurs at the rim of the column.

In a previous study, we focused on the chrominance pathways, and therefore we used an equiluminance green and red combination which we speculated that it would be processed by parvocellular cells. Our study's results suggested that the mechanism used to avoid incongruence between the retinal images of the eyes caused by occlusion occurs in the parvocellular cells (which process mainly color information) as well as in the magnocellular cells (which process binocular disparity) [14].

According to De Valois et al. [15], from the view of opponent color in L-, M-, and S-cone outputs, reddish blue (purple) and greenish-yellow (chartreuse) are base colors corresponding to the S-cone. In this context, 'purple' corresponds to the dominant wavelength of violet, which is located at the end point of the purple boundary in the 1931 CIE color space chromaticity diagram. We examined equiluminance using blue and yellow, since we focused on the characteristics of the S-cone (which has high sensitivity to the wavelength that corresponds to blue colors), and we chose yellow as the opponent color. It was reported that small bistratified cells give characteristic blue-on, yellow-off responses [11]. Here we describe our observation of the avoidance behavior of binocular eye movements when rim occlusion occurs at the rim of a column.

We made this article based on the contents which we announced in IMQA2018 [16].

2. Equiluminance Measurement

We first measured equiluminance for each subject in an experiment and then performed an occlusion experiment using values of measured equiluminance. The conditions used for Experiment 1 are summarized in Table 1. We measured the equiluminance for each of 10 human subjects by using the same equiluminance-measuring equipment as that in our previous study [5]. To elucidate the phenomena due to only chromatic information, it is necessary to measure the equiluminance that is not influenced by the luminance information. Here, we applied subjective equiluminance as in our previous study. The images used are shown in Figs. 2 and 3. At the starting point of the experiment, an image of black and green or black and yellow is presented on the computer's display monitor. The subject changes the red luminance setting on the keyboard until he or she concludes that the black panel provides the same luminance as the green panel (37.69 cd/m^2), which we set beforehand for an equiluminance experiment using green and red panels. Similarly, the subject changes the blue luminance setting until its luminance appears to be the same as that of the yellow panel (67.75 cd/m^2), which we set beforehand for an equiluminance experiment using yellow and blue panels. Location of each color on the CIE 1931 xy chromaticity diagram measured by a spectroradiometer (SR-LEDW-5N, TOPCON TECHNOHOUSE CORPORATION, Tokyo) shown in Fig. 4.

Table 1 Experiment 1 conditions.

Personal computer to generate image	SONY PCG-81314N
3D Display	Panasonic TH-P46VT2 (Plasma Display Panel)
Screen luminance	Max: 147.40 cd/m^2 Min: 1.93 cd/m^2 Green: 37.69 cd/m^2 Yellow: 67.75 cd/m^2
Illuminance	27 Lux

We used the upper-limit method and the lower-limit method for this measurement. The subjects adjusted red or blue from black by the upper-limit method and they adjusted red or blue from red with the maximum luminance or blue with the max. By the lower-limit method, they adjusted red or blue from black to achieve equiluminance. In this experiment, each of the two measurement methods were repeated five times each. We had each subject put on a black cloth to avoid the reflection of the subject's clothing on the display surface. When the numerical value of the equiluminance that a subject chose was stable, the numerical value was used for determining the average of the equiluminance values. This stability was defined as the time when a 'round trip' to the

Fig. 2 Equiluminance experiment: the luminance of the black panel is increased until equiluminance is reached.

Fig. 3 Equiluminance experiment: the luminance of the blue panel is decreased until equiluminance is reached.

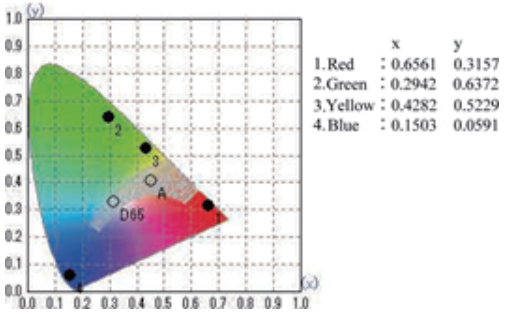

Fig. 4 Location of each color on the CIE 1931 xy chromaticity diagram.

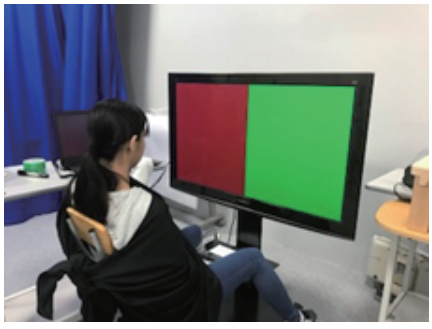

Fig. 5 The set-up for Experiment 1.

upper and lower limits of the same numerical value was observed. The viewing distance was 60 cm. The subjects were 10 university students (21–22 years old, 2 males, 8 females) with normal visual function and trichromatism. We confirmed that each subject had normal stereoscopic vision by asking them to observe a 3D image. A photo of the experimental set-up is given as Fig. 5. This experiment was conducted in accordance with the ethics regulations of Tokai University.

3. Equiluminance Results

The results of six subjects who were able to successfully measure the luminance value are summarized in Table 2.

The values that each subject judged as equiluminance is indicated by an R (red) or B (blue) value. The red values at equiluminance were 8–16 cd/m^2, and the maximum difference among the individual subjects was 8 cd/m^2. The blue values at equiluminance were 5–11 cd/m^2, and the maximum difference among the individual subjects was 6 cd/m^2. Figures 6 and 7 show the time course of typical examples over which subjects NKG, KYM, and KSM adjusted the settings to equiluminance.

4. Measurement of Convergence Eye Movement When Looking at Rim Occlusion

In this Occlusion experiment, we studied rim occlusion with a column as in our previous study [4], [5]. Figure 8 shows the five columns used. We created two types of columns in addition to the columns we used in the previous study: a white column for which occlusion does not occur at the rim; a colored column drawn by random dots with the equiluminance color for each subject obtained by experiment 1 and a colored column made of random dots with a non-equiluminance color.

The same set-up (Fig. 9) as that of Experiment 1 was used. The subject sat on a chair at 60 cm from the display and watched an example of rim occlusion through 3D liquid crystal shutter glasses. The experimental protocol is shown in Fig. 10. Three patterns were presented, in a specific order (Fig. 10). Pattern 1 in a red frame was a combination of the white column and one of the equiluminance columns. Pattern 2 in a green frame was a combination of the white column and one of the non-equiluminance columns. Pattern 3 in a blue frame was a combination of an equiluminance column and a non-equiluminance column. Each pattern was presented for 5 sec. We set the three patterns in a single loop, and we presented 10 loops in succession to each subject. The subjects were instructed to look at the right rim of the column. For 5 sec before and 5 sec after each column image presentation, a fixation point was presented in the center of the display. We used an eye tracking system (EMR-9, nac Image Technology Inc., Tokyo) to measure the subjects' eye movements.

5. Occlusion Results

We analyzed the data of 10 loops. We added the data of the 121 extracted samples of each loop in which the convergence eye movement became stable and averaged from the 5-sec periods when the columns were displayed.

We analyzed four subjects out of six subjects whose eye movement data was accurate since, because it was difficult to calibrate eye movement accurately in subject RSA and USU. Figures 11–14 illustrate the changes in the convergence angle

Table 2 Value and luminance of R and B values and at equiluminance.

Subject	RGB values judged as equiluminance (0-255)		Luminance judged as equiluminance (cd/m^2)	
	R	B	Red	Blue
SubNKG	186.0	232.4	16.03	11.53
SubKYM	150.0	170.0	8.80	5.16
SubAKT	158.0	172.0	8.58	5.89
SubKSM	180.9	196.0	12.59	7.08
SubRSA	143.9	218.6	7.57	10.14
SubUSU	167.8	170.8	12.37	5.24
Average	164.43	193.29	10.99	7.51

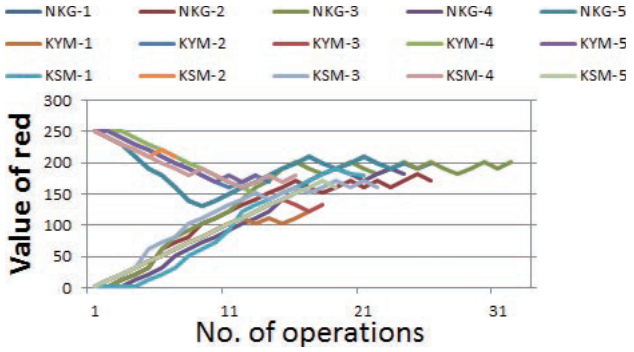

Fig. 6 Time course until red and green were considered to have the same luminance by subjects NKG, KYM, and KSM.

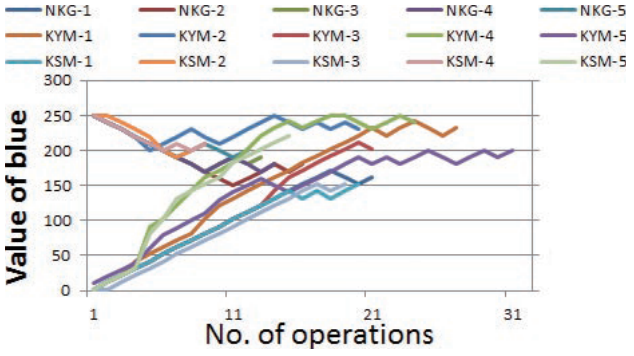

Fig. 7 Time course until yellow and blue were considered to have the same luminance by subjects NKG, KYM, and KSM.

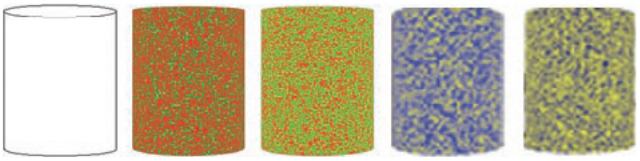

Fig. 8 The columns used in Experiment 2. From the left: white, non-equiluminance of red and green, equiluminance of red and green, non-equiluminance of yellow and blue, equiluminance of yellow and blue. (density of R: 0.57 deg/dot., density of G: 0.47 deg/dot., density of Y: 0.57 deg/dot., density of B: 0.47 deg/dot.).

for the red-green equiluminance protocol, and Figs. 15–18 show those for the yellow-blue equiluminance protocol. The standard deviation is indicated by error bars. The amount of change in the convergence angle differed between the red-green and yellow-blue equiluminance experiment in all

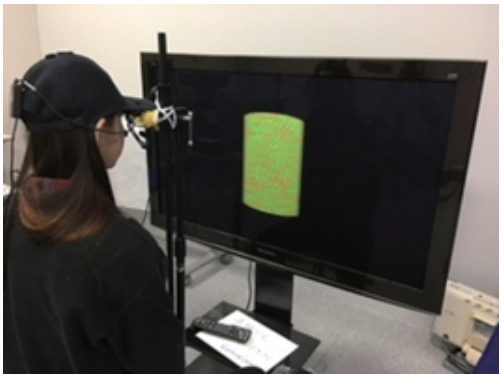

Fig. 9 The set-up for Experiment 2.

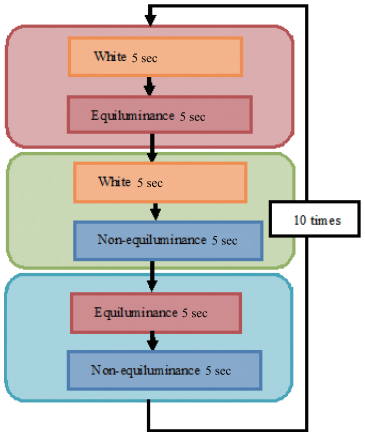

Fig. 10 Experiment 2: protocol.

four subjects. The convergence eye movement to evade both eyes' incongruence of the retinal image, i.e., whether both eyes moved inward or outward, depended on the individual observer. In some cases, the convergence angle increased.

These figures show that when the evasion action of eye movement to compensate for incongruence of the both retinal images by occlusion occurred at equiluminance from white, the convergence angle change; when the evasion action did not occur, the convergence angle did not change. The evasion action by convergence eye movement naturally occurs from white to the non-equiluminance due to the incongruence of the both retinal images. If evasion action in response to the incongruence of both retinal images by convergence eye movement occurs by equiluminance, evasion action would occur for both non-equiluminance and equiluminance. We

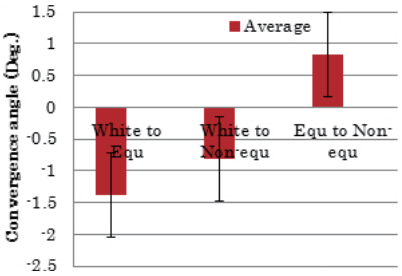

Fig. 11 Changes in the convergence angle for the red-green equiluminance protocol (subject NKG).

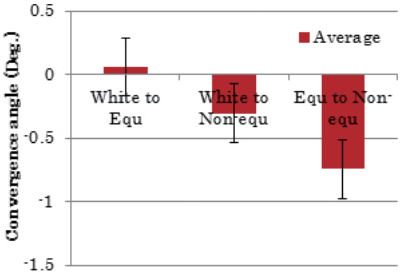

Fig. 12 Changes in the convergence angle for the red-green equiluminance protocol (subject KYM).

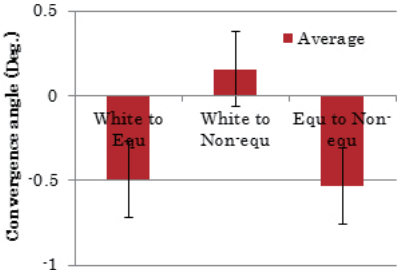

Fig. 13 Changes in the convergence angle for the red-green equiluminance protocol (subject AKT).

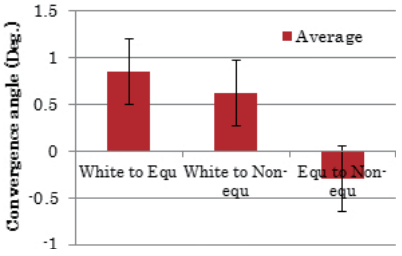

Fig. 14 Changes in the convergence angle for the red-green equiluminance protocol (subject KSM)

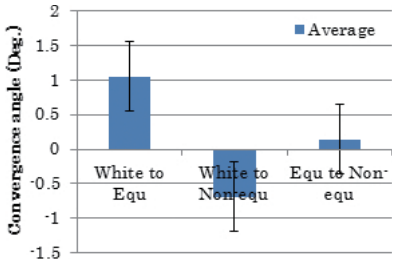

Fig. 15 Changes in the convergence angle for the yellow-blue equiluminance protocol (subject NKG).

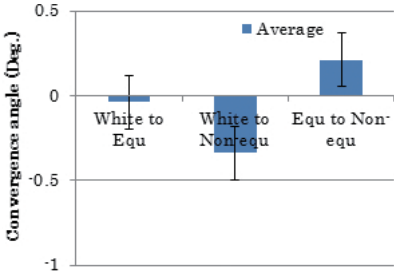

Fig. 16 Changes in the convergence angle for the yellow-blue equiluminance protocol (subject KYM).

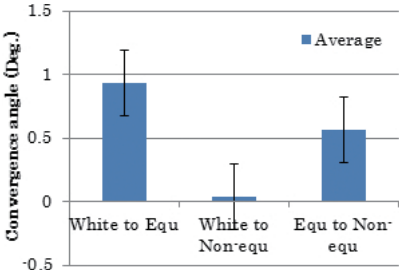

Fig. 17 Changes in the convergence angle for the yellow-blue equiluminance protocol (subject AKT).

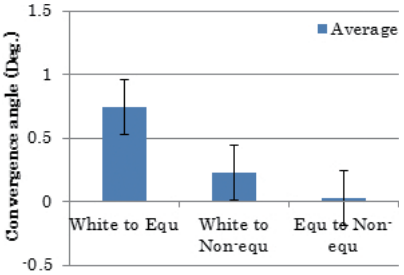

Fig. 18 Changes in the convergence angle for the yellow-blue equiluminance protocol (subject KSM).

thus consider two cases in which (1) the convergence angle changes only slightly, and (2) the convergence angle changes markedly.

6. Statistical Analysis Results

We statistically analyzed the response of the koniocellular cells, which would be involved in the convergence eye movement for the combination of blue and yellow. A change in the convergence angle was seen in all subjects. Because each eye makes miniature eye movements, the convergence eye movement changes consistently when gazing at the rim of a column. In consideration of changes caused by miniature eye movements, we used "Change, ○" when the convergence angle changed by $\geq 0.5°$ and "No change, ×" when the angle changed $< 0.5°$. Cases in which the convergence

Table 3 Cases in which the convergence angle changed ≥ 0.5° for the yellow and blue combination.

Subject	Equiluminance to white		Non-equiluminance to white		Equiluminance to non-equiluminance	
	○	×	○	×	○	×
SubNKG	6	4	6	4	3	7
SubKYM	2	8	7	3	5	5
SubAKT	8	2	5	5	7	3
SubKSM	10	0	7	3	3	7
SUM	26	14	25	15	18	22

Table 4 Cases in which the convergence angle changed ≥ 0.5° for the green and red combination.

Subject	Equiluminance to white		Non-equiluminance to white		Equiluminance to non-equiluminance	
	○	×	○	×	○	×
SubNKG	7	3	7	3	4	6
SubKYM	1	9	4	6	5	5
SubAKT	8	2	8	2	8	2
SubKSM	8	2	10	0	5	5
SUM	24	16	29	11	22	18

angle changed ≥ 0.5° are shown in Table 3. The data in the table revealed that the ratios in which the convergence angle changed by ≥ 0.5° were approximately. 65% from an equiluminance column to the white column, approximately. 63% from a non-equiluminance column to the white column, and approximately. 45% from a non-equiluminance column to an equiluminance column.

We conducted hypothesis testing for the population proportions (goodness of fit test) using the results described listed above (26/40, 25/40, 18/40) and the chance level of 50%. There were no significant differences: from a white column to the equiluminance column ($x^2(1) = 3.6, n.s.$), from a white column to the non-equiluminance column ($x^2(1) = 2.5, n.s.$), and from an equiluminance column to a non-equiluminance column ($x^2(1) = 0.4, n.s.$).

Next, to evaluate the response of the parvocellular cells, we analyzed the convergence eye movement for the combination of red and green. Table 4 summarizes the results. For the combination of red and green, there was no significant difference for between subjects NKG and KYM (NKG: $x^2(2) = 2.6, n.s.$, KYM: $x^2(2) = 5.38, n.s.$), but a significant difference was observed for between subjects AKT and KSM (AKT: $x^2(2) = 13.78, p < 0.05$, KSM: $x^2(2) = 11.32, p < 0.05$). We thus calculated the ratios in which the convergence angle of subjects AKT and KSM changed by ≥ 0.5°. The ratios were approximately. 90% from the white column to the equiluminance column, approximately. 60% from the white column to the non-equiluminance column, and approximately. 50% from the equiluminance column to the non-equiluminance column.

We conducted hypothesis testing for the population proportions (goodness of fit test) using the above results. From the white column to the equiluminance column ($x^2(1) = 12.8, p < 0.05$), from the white column to the non-equiluminance column ($x^2(1) = 0.8, n.s.$), and from the equiluminance column to the non-equiluminance column ($x^2(1) = 0, n.s.$). Because p-value of the values from the white column to the equiluminance column was < 5%, it turned out that there was a significant difference. Then, for the combination of red and green, there was significant difference "white column to the non-equiluminance column" ($x^2(1) = 8.1, p < 0.05$).

We compared the amount of change in the convergence angle for the combination of green and red with the amount of change in the angle for the combination of yellow and blue for each subject, using t-tests. These results are shown in Figs. 19–21. The result for the amount of change in the convergence angle from the white column to the equiluminance column for subject AKT (t(9)=2.225, p<0.05) only showed marginally significant level of 5% (we denoted a mark of '+' in graph), and the corresponding result for the white column to the non-equiluminance column of for subjects AKT and KSM showed significance level of 5% (AKT: t(9)=3.051, p<0.05 KSM: t(9)=2.52, p<0.05) (we denoted a mark of '*' in graph). The result for the change from the equiluminance column to the non-equiluminance column showed significance level of 5% only for Subject AKT (t(9)=2.833, p<0.05). Our analyses revealed that the convergence angle for the combination of green and red changed more significantly than that for the combination of yellow and blue. However, about subject KYM, the result of the non-equiluminance from equiluminance showed same tendency as that of other subjects, but the result of the non-equiluminance and equiluminance from white was very small. We consider this in the following chapter.

7. Discussion

Our equiluminance experiment demonstrated that the individual variance in the equiluminance of the yellow for the blue was smaller than the variance of the red for the green. We considered the following as the potential reasons for this result. Measurements of individuals' sense of color normalcy have shown that the S cones (blue cones) of the retinal visual cells account for 6% of all cones and that the individual difference in this value is small, whereas the reported percentages of M cones (green cones) and L cones (red cones) range from 52.7% to 94.3% of all cones, based

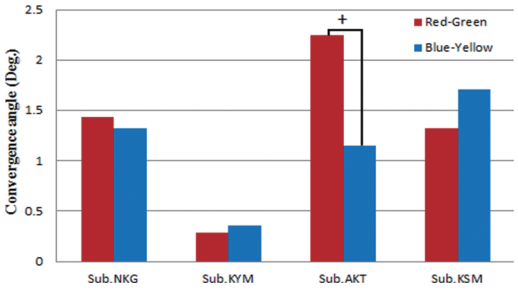

Fig. 19 Comparison of the amount of change in the convergence angle between the combination of green and red and the combination of yellow and blue for individual subjects (white to equiluminance).

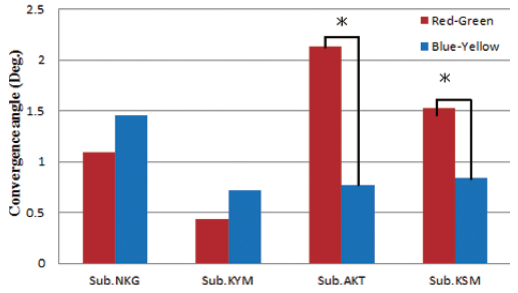

Fig. 20 Comparison of the amount of change in the convergence angle between the combination of green and red and the combination of yellow and blue for individual subjects (white to non-equiluminance).

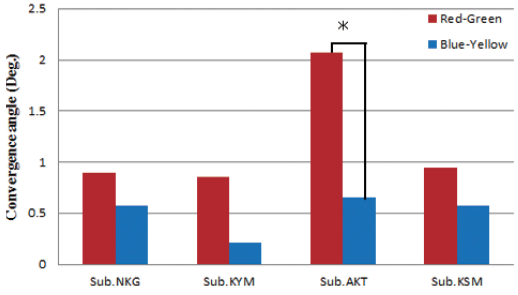

Fig. 21 Comparison of the amount of change in the convergence angle between the combination of green and red and the combination of yellow and blue for individual subjects (equiluminance to non-equiluminance).

on the evaluation of eight men [17], [18]. In other words, the individual difference in the equiluminance was small for S cones compared to those for M cones and L cones, and this may be a factor in our present findings.

Next, we discuss results of occlusion experiment. The reason why the results of combination of green and red showed significance difference while those of yellow and blue did a few is that change of convergence angle by yellow and blue was less than green and red. Further investigations are necessary to clarify whether subjects evade incongruence by occlusion by different means such as moving their focus or because they were unable to perceive incongruence of the retinal images by occlusion. About subject KYM, we think in particular that he might evade occlusion by these different means except eye movement.

We also speculate that the reason why the amount of change in the convergence angle for the combination of yellow and blue was smaller than that for the combination of green and red was the resolution of the koniocellular cell was low and the size of the random dots that we used was too small.

To say from the view of opponent colors, we used blue and yellow patterns as visual stimuli. We experience a multitude of mixed colors in our daily lives. For example, various colors are expressed by the CMY (cyan, magenta, yellow) color system in a printer or the RGB color system in a PC monitor. Conversely, any color is decomposed with other colors as bases. Yellow can be decomposed with components of greenish-yellow (chartreuse) and red. According to De Valois et al. [15], such color bases correspond to purple (+S vector) (chartreuse [−S vector] as an opponent color of purple) and to red (L-M vector) (the opponent color of red [M-L vector]). This implies that these color bases correspond to the koniocellular path response and the parvocellular path response. Accordingly, we would observe responses in the koniocellular and parvocellular pathways under these experimental conditions, since blue or yellow can be decomposed with purple (or chartreuse) and red (or the opponent color of red) components.

This result may indicate that occlusion detection by the combination of blue and yellow is more difficult compared to the combination of green and red. To test this idea, it could be informative to isolate the processing of both types of cells by using flickering random dot patterns, since the temporal resolution of parvocellular cells differs from that of koniocellular cells. We will seek to obtain definitive results with the use of the near colors of purple/chartreuse, which may result in an inhibition of the response of the parvocellular pathway.

In conclusion, our results suggest that the change in the convergence angle when gazing at rim occlusion differs between the combinations of green-red (processed by parvocellular cells) and yellow-blue (processed mainly by koniocellular cells), even when random dots of the same size are used.

8. Summary

In our experiment, the change in the convergence angle when the equiluminance column was used was not observed in the blue-yellow combination from a white column to the equiluminance column as observed in our previous study's use of a green-red combination. This suggests that people cannot detect or find it difficult to detect incongruence of both eyes' retinal images at equiluminance of yellow-blue, which koniocellular cells process. Further investigations are necessary to test this possibility. The Modulation Transfer Function (MTF) of the yellow - blue has much more low pass characteristics than MTF of the red - green.

In other words, it is possible that the random pattern that we used in this study was beyond the spatial resolving power of the koniocellular cells. By changing the size of the random dot, it is necessary to check an evasion action

by convergence eye movement at the much lower spatial frequency.

Our study also included on subject with a small change in the convergence angle. Several reasons for this can be considered. It may have been difficult for the subject to detect incongruence of the retinal images by occlusion, or to focus on the rim of the columns by accommodation; alternatively, the subject may have gazed at the rim by using a more superior/ dominant eye and neglected the non-dominant eye information, or the subject's eyes. Many psychophysical experiments on the comparison between parvocellular cells and magnocellular cells ones have been performed, but there are few experiments on koniocellular cells and on the comparison between parvocellular cells and koniocellular cells ones. As a result of this experiment, we were able to suggest the possibility that we could evaluate the difference between parvocellular cells and koniocellular cells ones objectively from an evasion action by the occlusion.

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